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THERMAL MODEL OF A 75 WATT(E) SPACE POWER PLANAR RTG SYSTEM

ANDREW J. PARKER, JR.
WILLIAM S. WEST

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GREENBELT, MARYLAND

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THERMAL MODEL OF A 75 WATT(E) SPACE POWER PLANAR RTG SYSTEM

Andrew J. Parker, Jr.*
Project Engineer

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Technical Staff

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GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

*Hittman Associates, Inc., Columbia, Maryland

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ABSTRACT

This paper describes the preliminary work accomplished on an advanced thermoelectric design concept for NASA.* This concept has possible application to deep space missions and may offer additional flexibility in the integration of a power supply with spacecraft. The concept differs from conventional omnidirectional thermal radiator devices in that it uses a planar, unidirectional or bidirectional, radiator. The accomplishments include design, fabrication, and test of a full size thermal model to establish feasibility of the concept.

*RCA Prime Contract NAS5-10441, Hittman Associates P. O. GX-F76000-0001-F29.

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CONTENTS

ILLUSTRATIONS

Figure		Page

THERMAL MODEL OF A 75 WATT(E) SPACE POWER PLANAR RTG SYSTEM

I. INTRODUCTION

The NEW MOONS (NASA Evaluation With Models of Optimized Nuclear Spacecraft) thermal model is a full scale model of a planar type radioisotope thermoelectric generator (RTG). (A planar RTG is defined as one which rejects its waste heat unidirectionally; i.e., its radiator is oriented in a preferred direction (plane). Further, the thermopile is presumed to be attached to the radiator and to lie in the radiator plane. Thus, the potential for utilizing the heat source energy is limited to one direction. The design concept departs from the more traditional, cylindrically shaped, RTG which rejects its waste heat omnidirectionally.) Figure 1 is a photograph of the completed system. The envelope dimensions of the thermal model are as follows:

- Radiator — 32 inches square

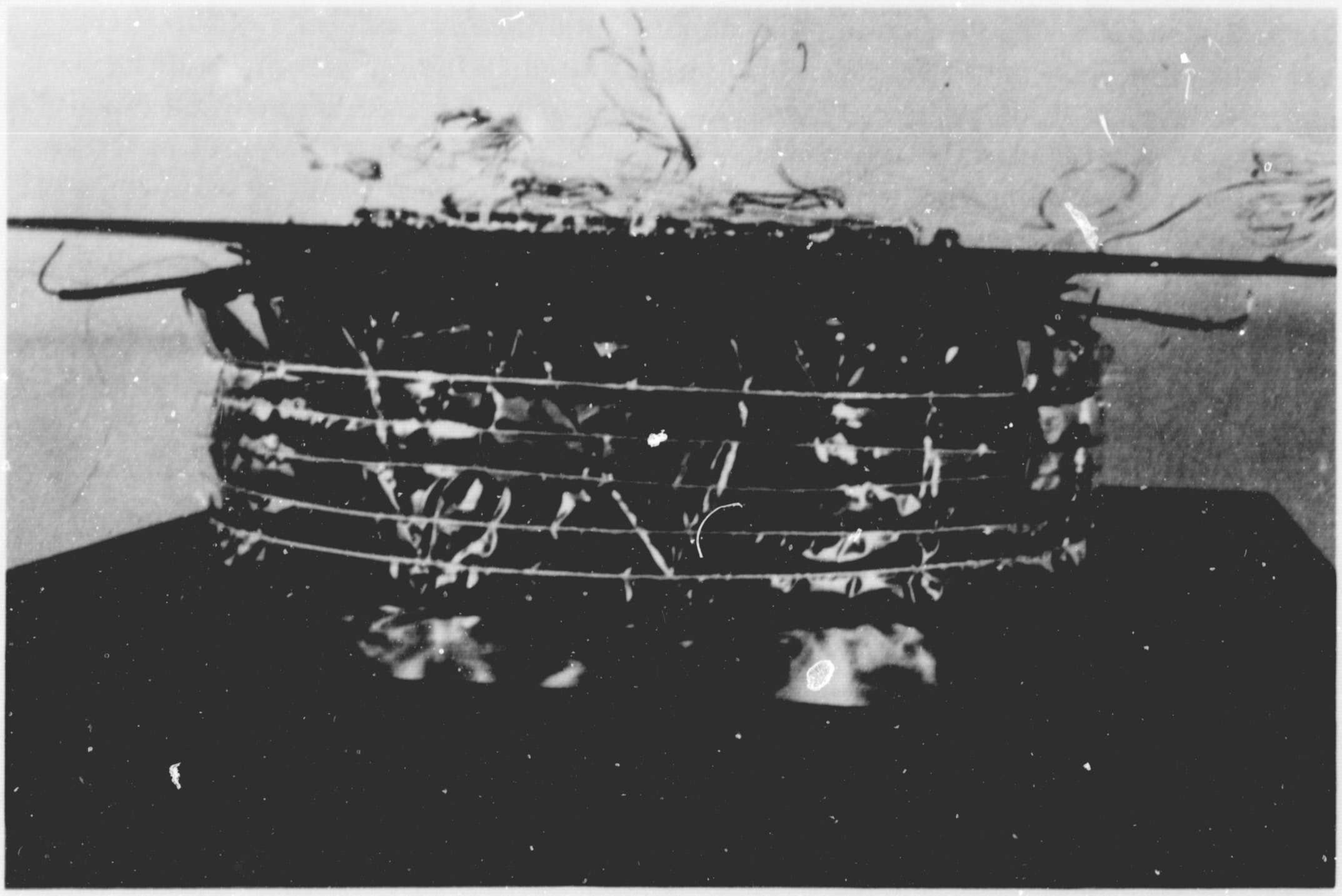

Figure 1. NEW MOONS Thermal Model

- Depth — 6.75 inches (top of the radiator to the bottom of the heat source basket)

- Heat Source Basket — 17.75 inches in diameter

The basis for the design is a 75 watt electric (end-of-mission-life, five years) RTG. The discussion that is presented in this paper is limited to the design, fabrication, and testing efforts performed to establish feasibility of the concept.

The thermal model incorporates, to the extent that is considered to be practical and economic, materials of construction that would be used in a flight type RTG system. The radiator, for example, is fabricated in one piece from a block of hot-pressed beryllium. A noble metal (platinum) multifoil vacuum type thermal insulation basket is used to maintain the thermal losses from the rear (or spacecraft) side of the heat source basket to a minimum. (The calculated thermal losses through this component are about 150 watts, or less than 10 percent of the total thermal inventory.) In addition, Dyna-Quartz, Micro-Quartz felt, and Min-K-2020* insulations are used at critical thermal locations within the thermal model assembly. The unit is adequately instrumented. The 112 couple thermopile includes a 2 × 6 couple, Air-Vac, silicon-germanium (SiGe) thermoelectric module† to demonstrate the power generation capability of the NEW MOONS system. The remaining 100 couples are thermal analogs of the SiGe couples. The NEW MOONS thermopile assembled to the beryllium radiator is shown in Figure 2. A platinum resistance heater unit was designed and developed by Hittman Associates for the model. The heater, which is capable of both air and vacuum operation at a surface temperature of about 2000°F, proved to be satisfactory for the system test program. In summary, the utilization of the above mentioned components, packaged into a planar radiator configuration, yields a system that is unique.

II. DISCUSSION

A discussion of the more important components of the thermal model follows.

A. Beryllium Plate

The design drawing, 859, Figure 3, reflects the as-built status of the radiator. The component was fabricated from an as hot pressed beryllium block (the

*Johns-Manville.
†Fabricated by RCA-ECD.

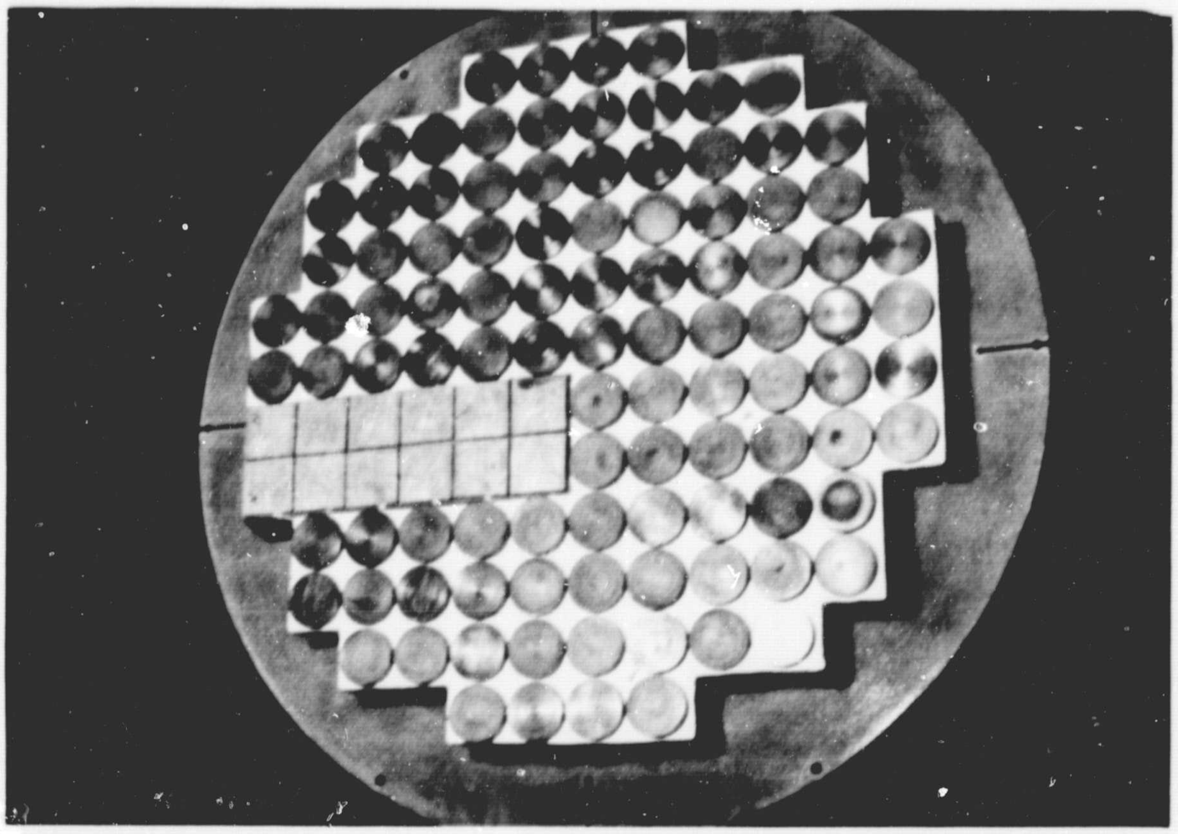

Figure 2. NEW MOONS Radiator Assembly–Heat Source Side

Brush Beryllium Company's certification of material S-200-E, Type I). To ensure structural integrity, four slots (0.050 inch by nine inches long) were machined into the plate. Subsequent to the machining operations, the radiator was chemically etched to remove surface twinning. The completed plate was black anodized to raise its emissivity value. As a final fabrication operation, the radiator was stress relieved at a temperature of about 1450°F for one-half hour and then air quenched. Several of the operations that were performed on this component are unique when considering the plate size. These are:

- Black anodizing (Figure 4)
- Chemical etching to a close tolerance (~0.002 inch)
- Brazing of other materials to beryllium (Figure 5)

The black anodizing resulted in a measured emissivity value of 0.915 at 500°C and 0.875 at 300°C.

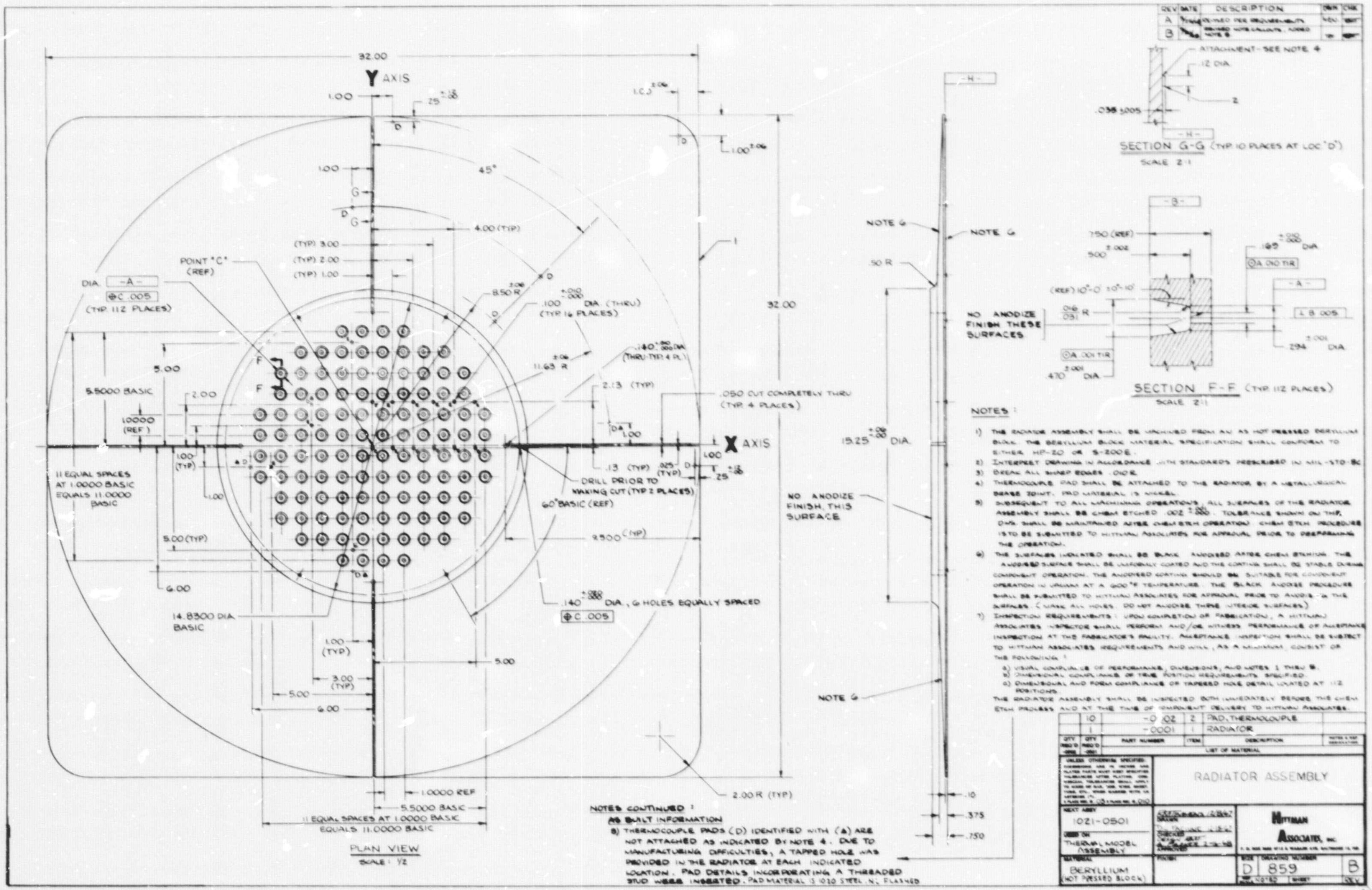

Figure 3. Radiator Assembly

Figure 4. Plate After Anodizing, Fixture Still Attached

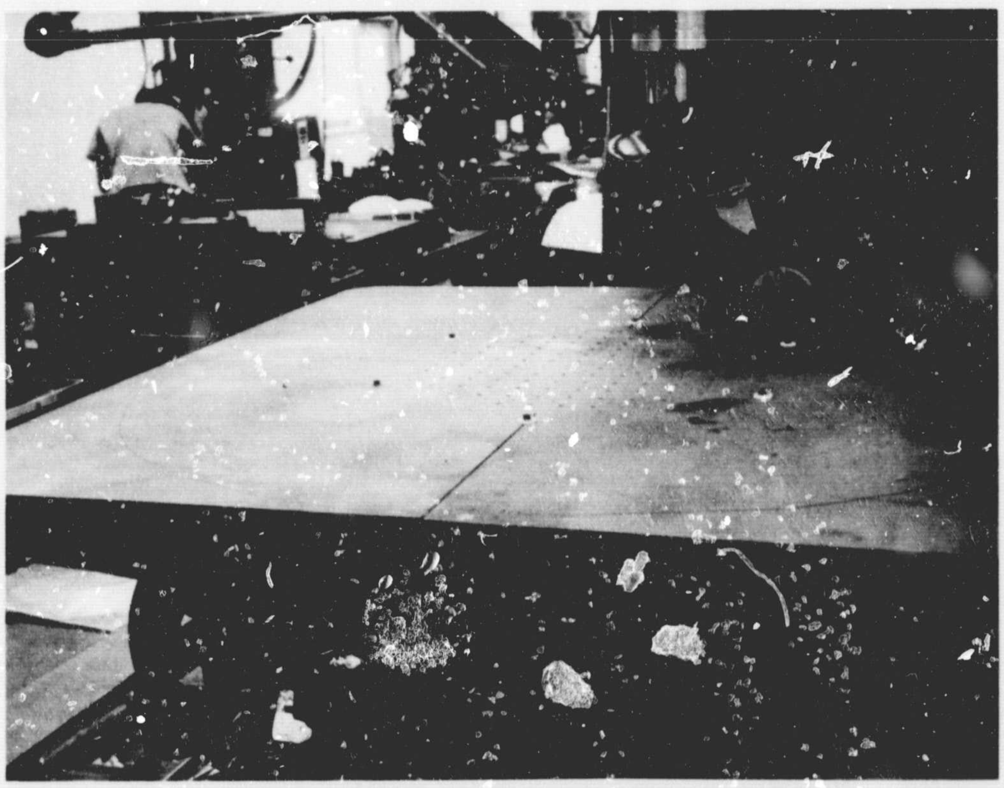

Figure 5. Brazing Operations Completed
(Tape Jig-Bore Machine in the Background)

B. Active Thermoelements

The active thermopile includes 12 SiGe thermocouples of the RCA Air-Vac design that are connected electrically in a series-parallel configuration. The completed module is shown in Figure 6. The design, fabrication, and assembly of this module was performed by RCA-ECD. The module is designed to deliver about 9.5 watts (electric) power when the average hot junction temperature is 1490°F and the average radiator temperature at the cold junction interface is 509°F. The calculated temperature drop across the cold junction/radiator interface is approximately 50°F. The expected module efficiency (when it is operating between these two temperature limits) is 5.17 percent.

C. Thermal Analog Units

Of the 112 thermocouple locations, 100 are filled with thermal analogs (Figure 7). These units are fabricated from 1020 carbon steel. The carbon steel material was selected on the basis of its excellent thermal expansion match to beryllium over the operating temperature range of interest (room temperature to about 600°F). The unit is designed to conduct the same amount of heat to the radiator as a SiGe thermocouple when it is subjected to an identical temperature differential ($T_{hot\ junction} - T_{radiator}$). Thus, only the end point temperatures match (as well as the heat flow) and not the intervening temperature gradient. The completed units were nickel flashed to prevent surface oxidation subsequent to component assembly.

The mode of heat transfer between the heaters and the thermoelements is by radiation. To maximize the efficiency of this process, the radiating and the receiving surfaces must be as near a black body (ϵ = 1.0) as possible. The nickel plated analog units (ϵ = 0.35) were oxidized with an oxygen rich gas mixture. In this manner, a relatively uniform surface coating was obtained which has a measured surface emissivity of about 0.7 at the shoe operating temperature (1490°F).

D. Vacuum Insulation Assembly

The vacuum insulation assembly design details are presented by Hittman Associates' Drawing 874 and Thermo Electron Corporation Drawing 203P-1000 (Figures 8 and 9). The assembly consists of the following components.

- Haynes-25 inner containment basket
- Multi-foil insulation assembly, forty foil layers
- Stainless steel (304) outer containment basket
- Stainless steel (304) bottom closure plate

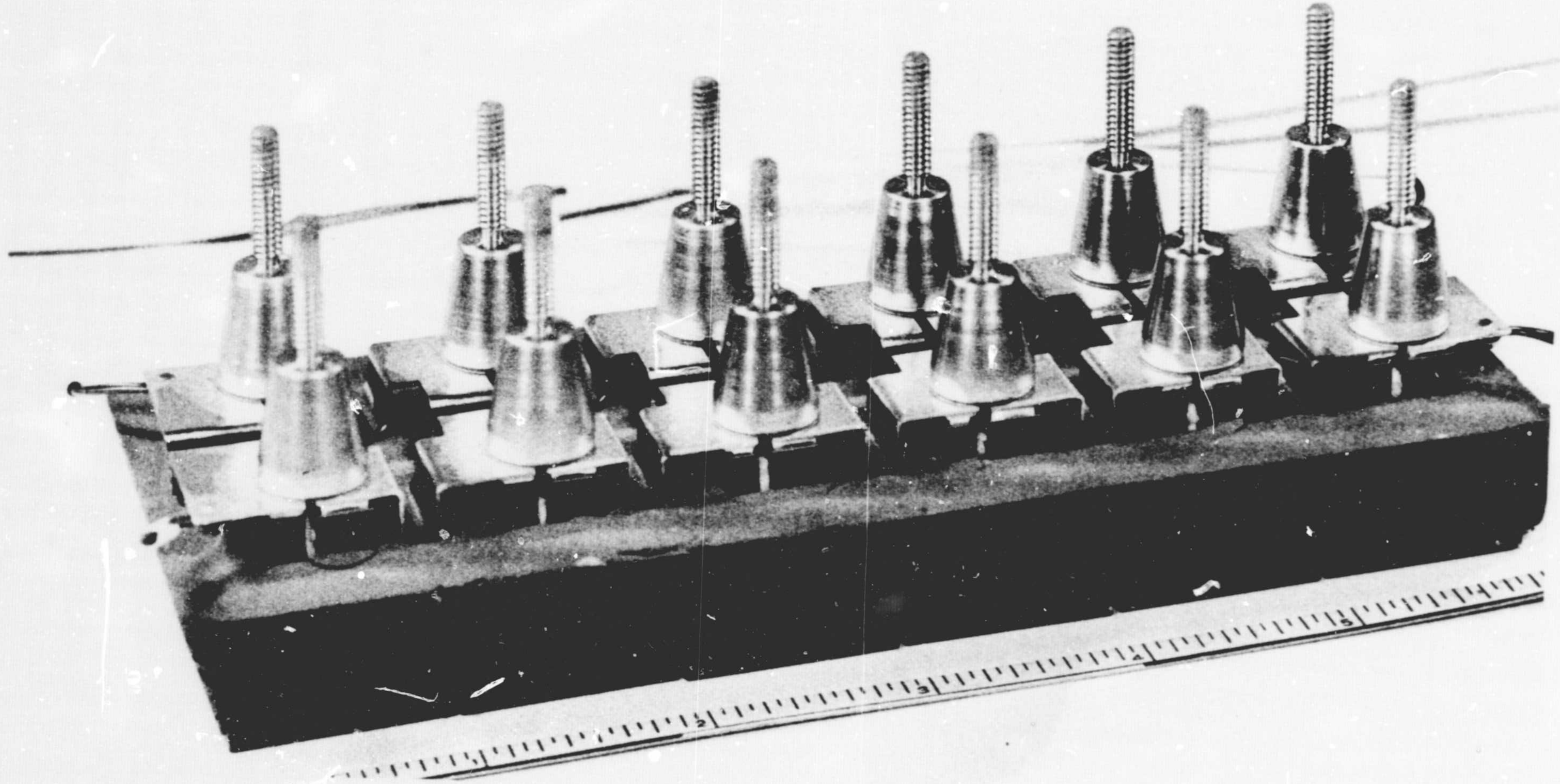

Figure 6. RCA-ECD 2 × 6 SiGe Module

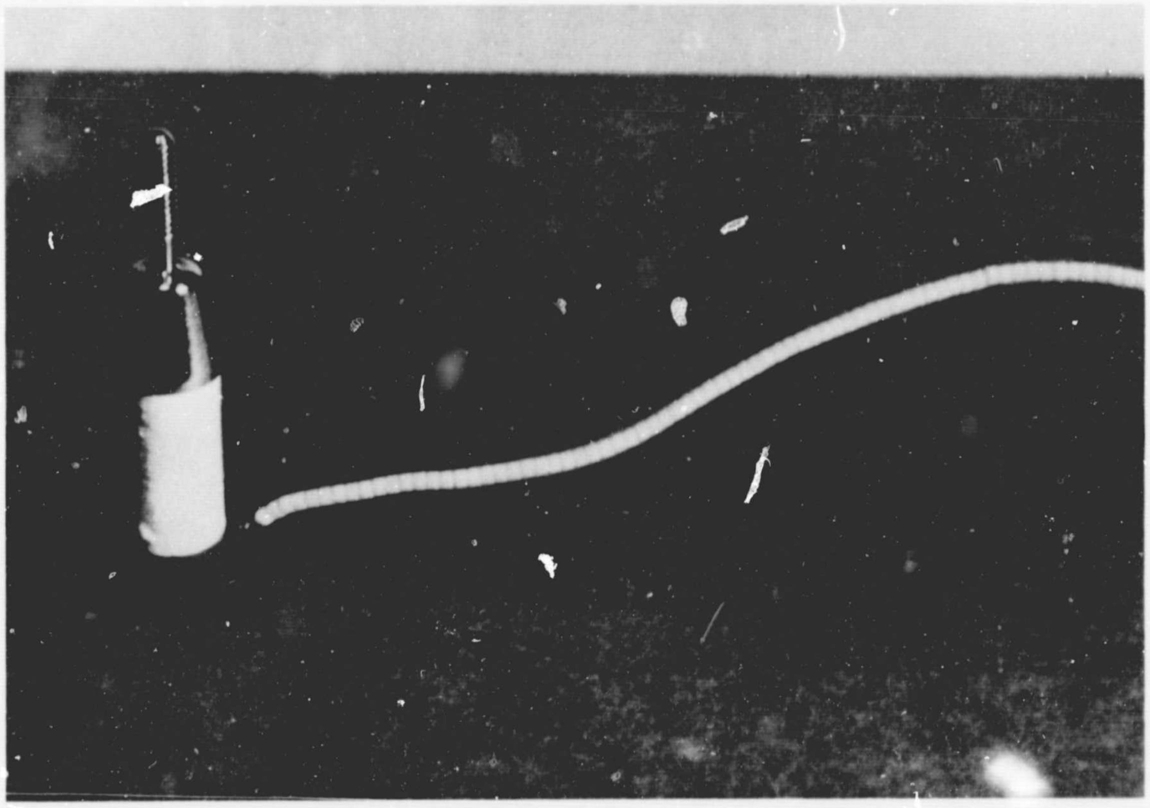

Figure 7. Instrumented Dummy Thermoelement

This component is unique. It is the largest planar configuration, multi-foil insulation assembly that has been fabricated to date that can be subjected to both air and vacuum operation at high temperature. The design of this component is based on the following additional design criteria:

- The inner surface temperature is 1700°F
- The outer surface temperature is 400°F
- The total heat loss in a vacuum cannot exceed 150 watts
- The component is not to be an expendable item for this test program
- Inadvertant vacuum chamber shutdown is to be anticipated (thus operation in an air environment at 1700°F is to be expected)

A noble metal, platinum, was selected as the foil material. (The use of platinum is justified because it exhibits stable emissivity characteristics at temperatures up to 1700°F in either air or vacuum and because of its oxidation resistance during air operation.) The platinum foil is 0.00025 inch thick per layer. Each layer is sprayed with zirconia during the assembly operation. The foil layers are grouped as shown in Figure 9. The base consists of 40 planar

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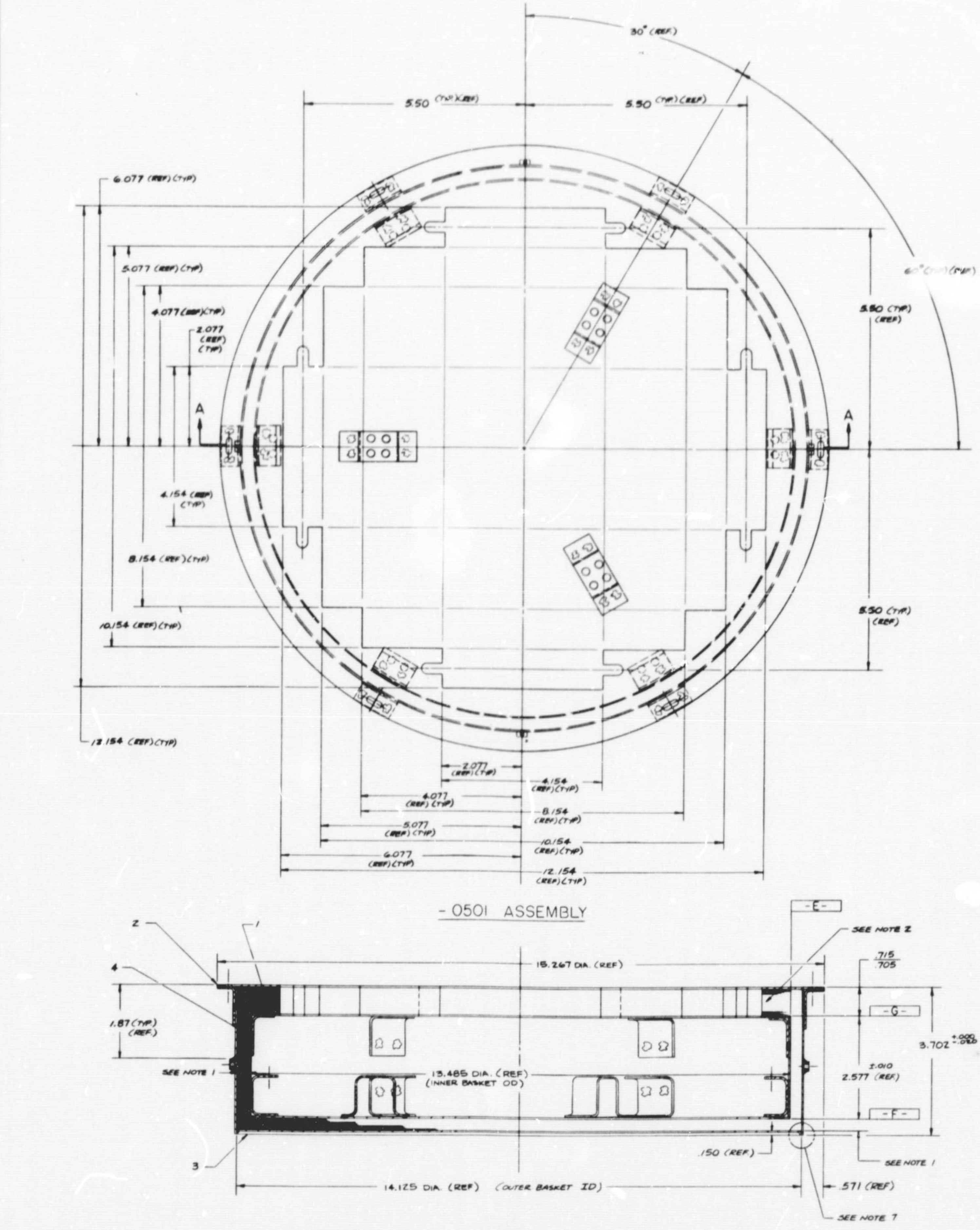

NOTES:

1) INNER BASKET SURFACES E AN…
PLATINUM OR EQUIVALENT FO…
LAYERS OF SEPARATION MATER…
2) THE NUMBER OF ALTERNATELY …
INSULATION LAYERS AND SE…
BASKET SURFACE G SHALL…
DIMENSION .715/.705 A…
3) INSULATION HORIZONTAL TO…
FOR REFERENCE PURPOSES…
FABRICATORS REQUIREMENT…
4) THE INSULATION ASSEMBLY S…
INTERNAL SURFACE TEMPER…
TEMPERATURE AT 400 °F W…
SHALL BE CAPABLE OF OPER…
OF OPERATION IN AIR WITH…
WITHOUT CHANGING THE VA…
CHARACTERISTICS.
5) THE INSULATION BASKET AS…
DIFFERENTIAL THERMAL E…
OPERATING TEMPERATURE W…
15 POUNDS AND AN EXTER…
COMPROMISING THE THERMA…
ASSEMBLY.
6) THE ASSEMBLY SHALL BE CAP…
SHIPMENT AND ASSEMBLY …
7) FABRICATOR SHALL PERFORM…
AREA. WELD CONFIGURATIO…
REQUIREMENTS OF THE ASSE…
8) ITEMS 1, 2, AND 3 SHALL B…
ARE FABRICATED FROM THE …
ITEM 1 - HAYN…
ITEMS 2 AND 3 - …
9) THE DESIGN OF THE INSULATI…
REVIEW BY HITTMAN ASSOC…
FABRICATION.

FOLDOUT FRAME # 1

FOLDOUT FRAME

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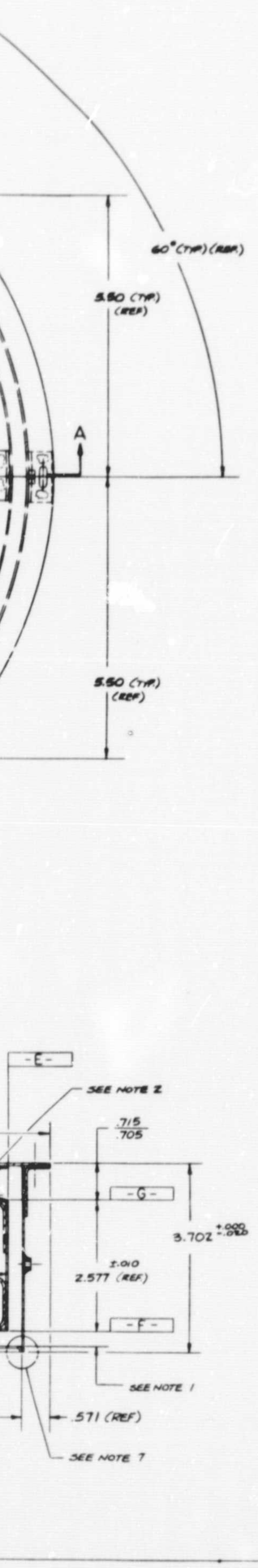
A	[illegible]	REVISED DRAWING TO "AS BUILT" CONDITION.	[illegible]	



NOTES:

1) INNER BASKET SURFACES E AND F SHALL BE INSULATED USING LAYERS OF PLATINUM OR EQUIVALENT FOIL TYPE INSULATION ALTERNATELY ASSEMBLED WITH LAYERS OF SEPARATION MATERIAL.
2) THE NUMBER OF ALTERNATELY ASSEMBLED PLATINUM OR EQUIVALENT FOIL TYPE INSULATION LAYERS AND SEPARATION MATERIAL LAYERS AT THE INNER BASKET SURFACE G SHALL BE SELECTED TO YIELD THE NON-LOAD DIMENSION .715/.705 AND TO PROVIDE A FIRM INSULATION ASSEMBLY.
3) INSULATION HORIZONTAL TO VERTICAL INTERSECT JOINT DESIGN SHOWN IS FOR REFERENCE PURPOSES ONLY AND MAY BE MODIFIED PER FABRICATORS REQUIREMENTS.
4) THE INSULATION ASSEMBLY SHALL BE DESIGNED FOR VACUUM OPERATION WITH INTERNAL SURFACE TEMPERATURE AT 1700 °F AND EXTERNAL SURFACE TEMPERATURE AT 400 °F WITH HEAT LOSS NO GREATER THAN 150 WATTS AND SHALL BE CAPABLE OF OPERATION TO 1900 °F. DESIGN SHALL BE CAPABLE OF OPERATION IN AIR WITH AN INTERNAL SURFACE TEMPERATURE OF 1700 °F WITHOUT CHANGING THE VACUUM OPERATION HEAT TRANSFER CHARACTERISTICS.
5) THE INSULATION BASKET ASSEMBLY MUST BE CAPABLE OF WITHSTANDING DIFFERENTIAL THERMAL EXPANSION FROM ROOM TEMPERATURE TO OPERATING TEMPERATURE WHILE SUPPORTING AN INTERNAL LOAD OF 15 POUNDS AND AN EXTERNAL LOAD OF 15 POUNDS, WITHOUT COMPROMISING THE THERMAL AND STRUCTURAL REQUIREMENTS OF THE ASSEMBLY.
6) THE ASSEMBLY SHALL BE CAPABLE OF REASONABLE HANDLING DURING SHIPMENT AND ASSEMBLY AT ROOM TEMPERATURE CONDITION.
7) FABRICATOR SHALL PERFORM TIG OR EQUIVALENT CLOSURE WELD IN THIS AREA. WELD CONFIGURATION AND QUANTITY MUST MAINTAIN STRUCTURAL REQUIREMENTS OF THE ASSEMBLY.
8) ITEMS 1, 2, AND 3 SHALL BE PROVIDED BY HITTMAN ASSOCIATES, INC AND ARE FABRICATED FROM THE FOLLOWING MATERIALS:
   ITEM 1 - HAYNES ALLOY NO 25
   ITEMS 2 AND 3 - 304 L STAINLESS STEEL
9) THE DESIGN OF THE INSULATION BASKET ASSEMBLY SHALL BE SUBJECT TO REVIEW BY HITTMAN ASSOCIATES, INC. PRIOR TO INITIATION OF FABRICATION.

QTY REQ'D	QTY REQ'D	PART NUMBER	ITEM	DESCRIPTION	NOTES & REF
	X		4	INSULATION	
	1	886-0501	3	CLOSURE PLATE	
	1	881-0501	2	OUTER BASKET ASSY.	
	1	875-0501	1	INNER BASKET ASSY.	

LIST OF MATERIAL

INSULATION BASKET ASSY.

NEXT ASSY: 1022-0501

USED ON: GENERATOR TEST ASSEMBLY

HITTMAN ASSOCIATES, INC.

E 874 A

Fold OUT

Figure 8. Insulation Basket Assembly

#2

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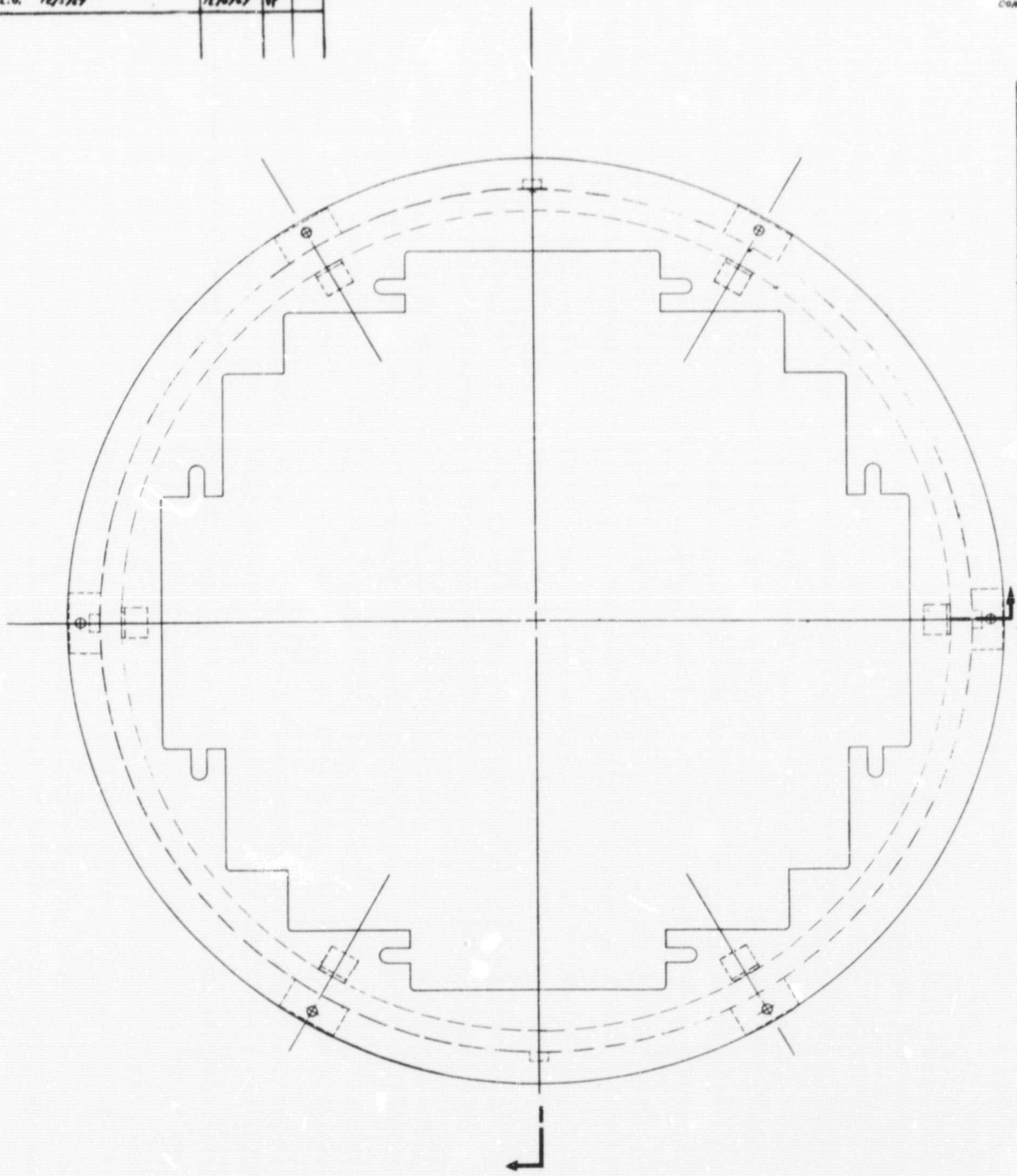

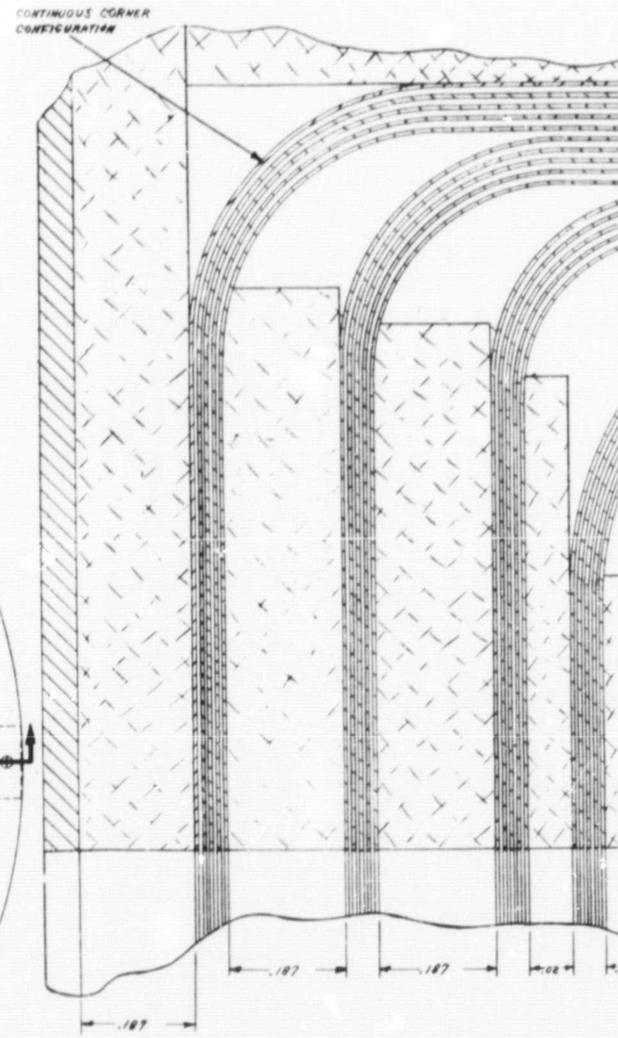

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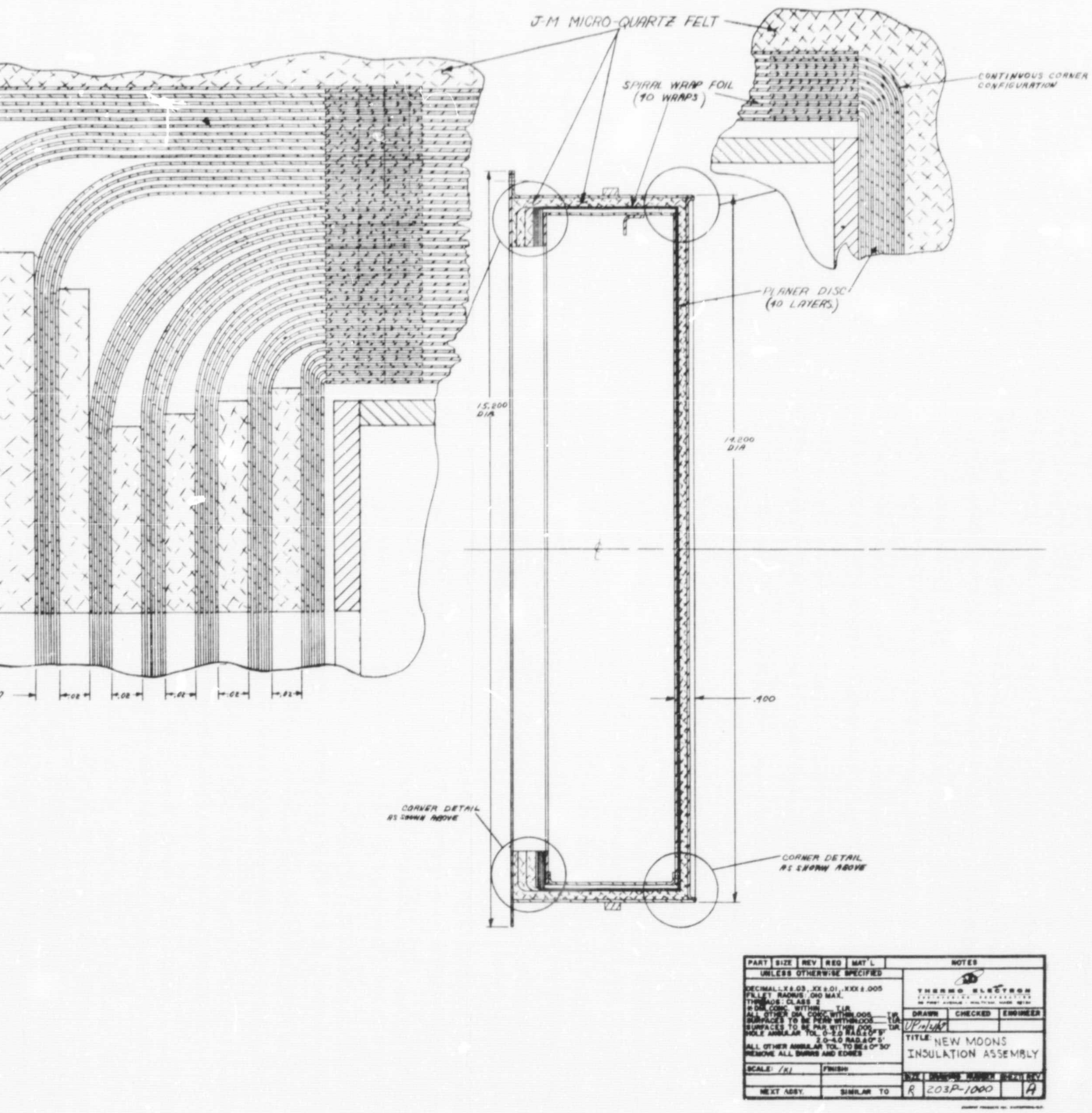

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Figure 9. NEW MOONS Insulation Assembly

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discs layered one on top of the other. Interwoven with these layers at the corners is a continuously spiral wrapped (40 layers) side construction. The top corners (the areas under the beryllium radiator) are constructed in groups of five foil layers. Each set of foil layers is separated from the next set with Micro-Quartz felt. The separation distances vary to produce a near linear temperature gradient from the inside to the outside surfaces of the assembly to match approximately the temperature drop through the thermopile. The foil assembly is constructed around the inner basket, wrapped with Micro-Quartz felt, and completed with the placement and welding of the outer basket and bottom plate. Some of the details of this assembly are presented in Figures 10 and 11. The vertical central rod that is seen in Figure 11 is a part of a tool that is used to keep forces that are exerted on the inner basket during fabrication from being transmitted into the insulation assembly. This tool was also useful during subsequent handling and shipping operations.

E. Thermal Model Heaters

The primary component of the NEW MOONS thermal model is the heat source. The heat source design criteria are summarized as follows:

- Maximum voltage—25 volts

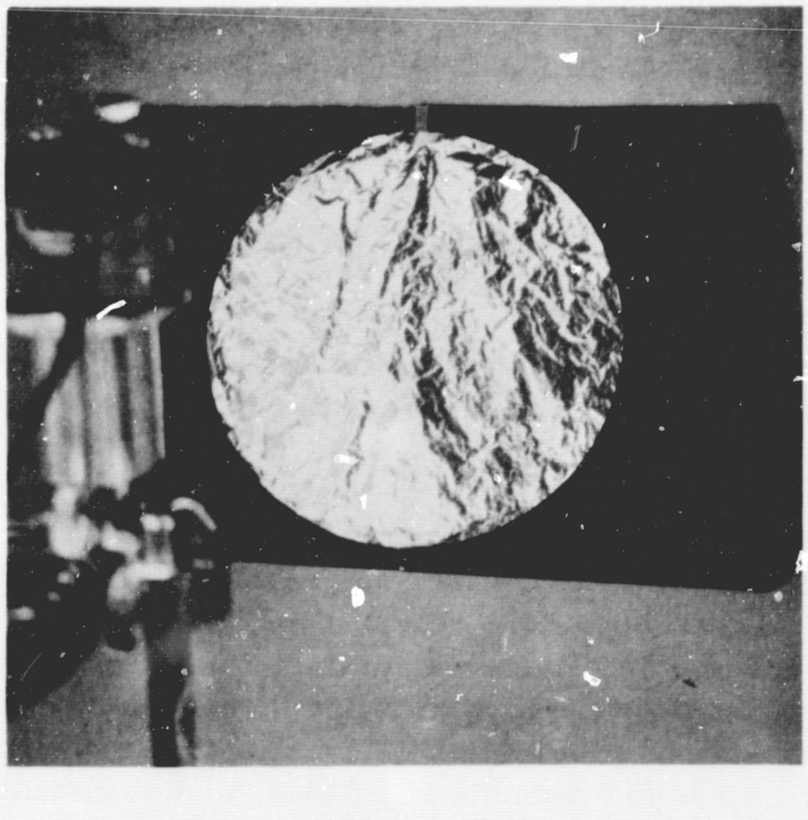

Figure 10. Platinum Insulation Assembly–Spray Coating the Bottom Planar Discs

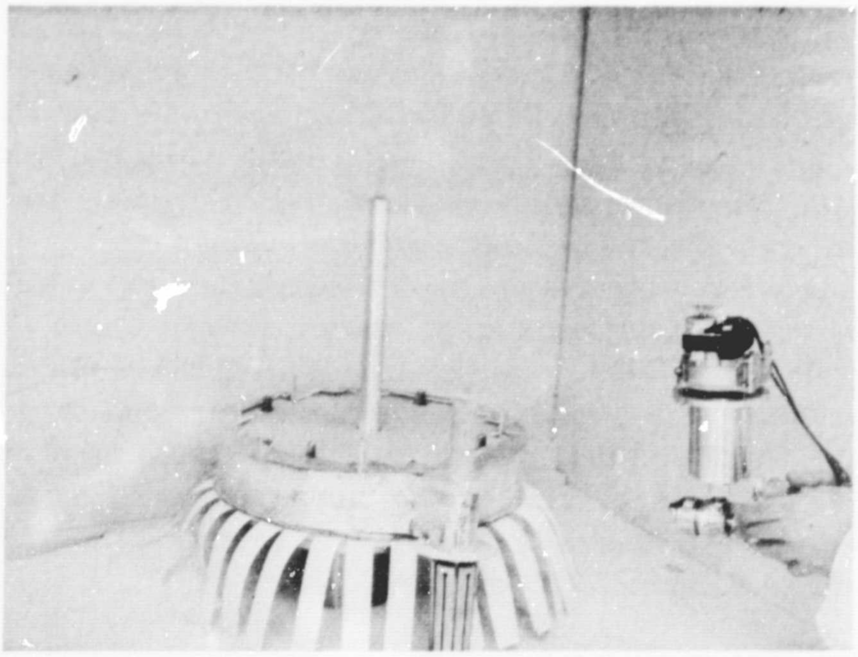

Figure 11. Final Assembly of the Platinum Insulation Assembly

- Maximum operating temperature—2000°F
- Power density—44 watts/in^2
- Wire—0.032 inch diameter, platinum 10 percent rhodium, totally enclosed. The wire is to be helically wound. Provide four inch long leads covered with high purity Al_2O_3. The heater encasement shall be high purity (99 ± percent) alumina.

The selected heater is shown in Figure 12 with the top face removed for clarity. Figure 13 is an x-ray of a heater after many hours of operation at the design specification values.

Proof-of-design principle was demonstrated through many hours of operation in both air and vacuum environments. A total of about 5000 heater test hours were accumulated during the evaluation program. Alumina has a low emissivity ($\epsilon \approx$ 0.2 to 0.3). Therefore, to improve the efficiency of the radiation heat transfer process from the heaters to the thermoelement hot shoes, the surface emissivity must be increased. Thus, a second objective of the heater evaluation program was to determine a suitable surface coating for the heaters.

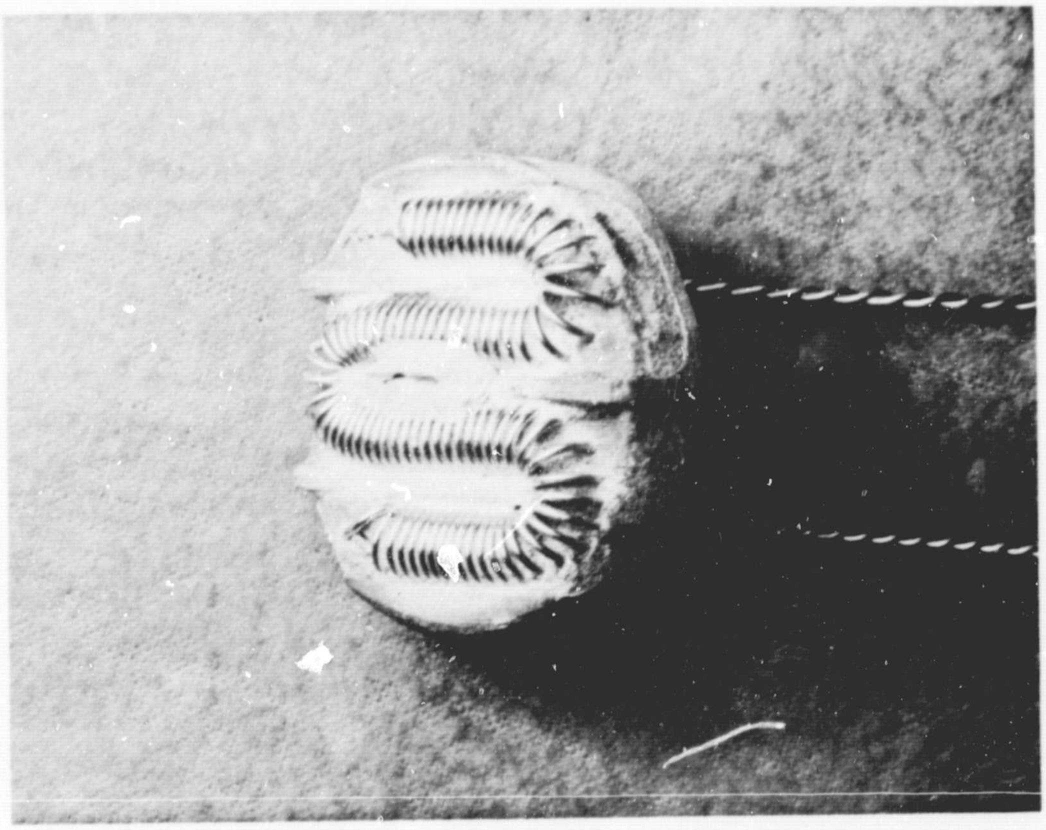

Figure 12. NEW MOONS Thermal Model Heater-Top Face Removed

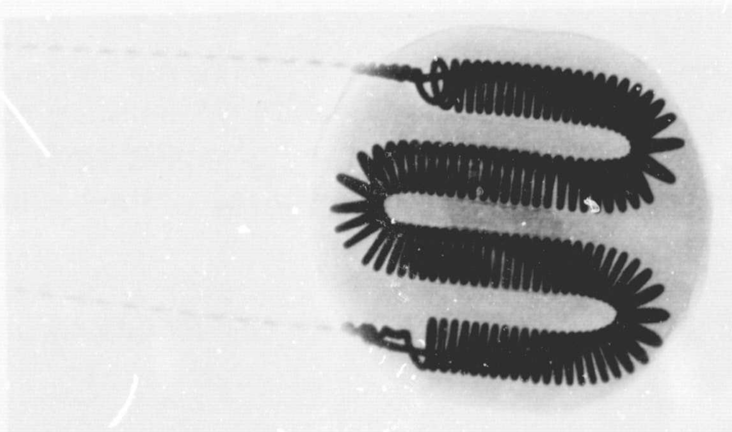

Figure 13. X-Ray of Heater After Rated Service

The result of this phase of the effort was to select TiO_2 as the surface coating ($\epsilon \approx 0.7$). The material is flame sprayed onto the heater surface prior to assembly. The TiO_2 in the as-sprayed condition is a blue-gray color. After some hours of operation (50 to 75) at a temperature in excess of 1700°F, the surface color changes to a dull orange. However, no performance variations were observed from this color change during the evaluation tests (i.e., the apparent surface emissivity remained at a value of about 0.7).

Nineteen heaters are used in the final assembly. They are wired into five heating zones as shown on Figure 14. Figure 15 shows the heater zones being installed into the insulation basket. (The photograph was taken prior to installing the final heater zone.) It can be observed that the bottom surface of the insulation basket is covered with a shaped section of 1/4 inch thick Dyna-Quartz insulation. The heater assemblies are installed according to the procedure described on Figure 16. They are attached to clips in the insulation basket with Haynes-25 wire (see Figure 15). One heater in each zone is used for zone control through a temperature monitor. A redundant temperature pick-up on these heaters is run to a separate recorder and used to obtain the heater temperature history.

F. Miscellaneous Hardware

The additional hardware that is used in the thermal model consists of:

- Gold foil
- Heater base plates of Haynes-25 (TiO_2 is flame sprayed onto the heater base plates prior to final assembly to increase their emissivity value)
- Insulation—Dyna-Quartz, Micro-Quartz felt, Min-K-2020, and alumina beads
- Platinum—10 percent rhodium heater zone leads and interconnecting wiring
- Thermocouples—Platinum—10 percent rhodium and chromel-alumel, and tungsten-tungsten-rhenium
- Aluminum basket
- H-Film (plastic product that is suitable for relatively high temperature operation, ~400°F)
- Attachment hardware

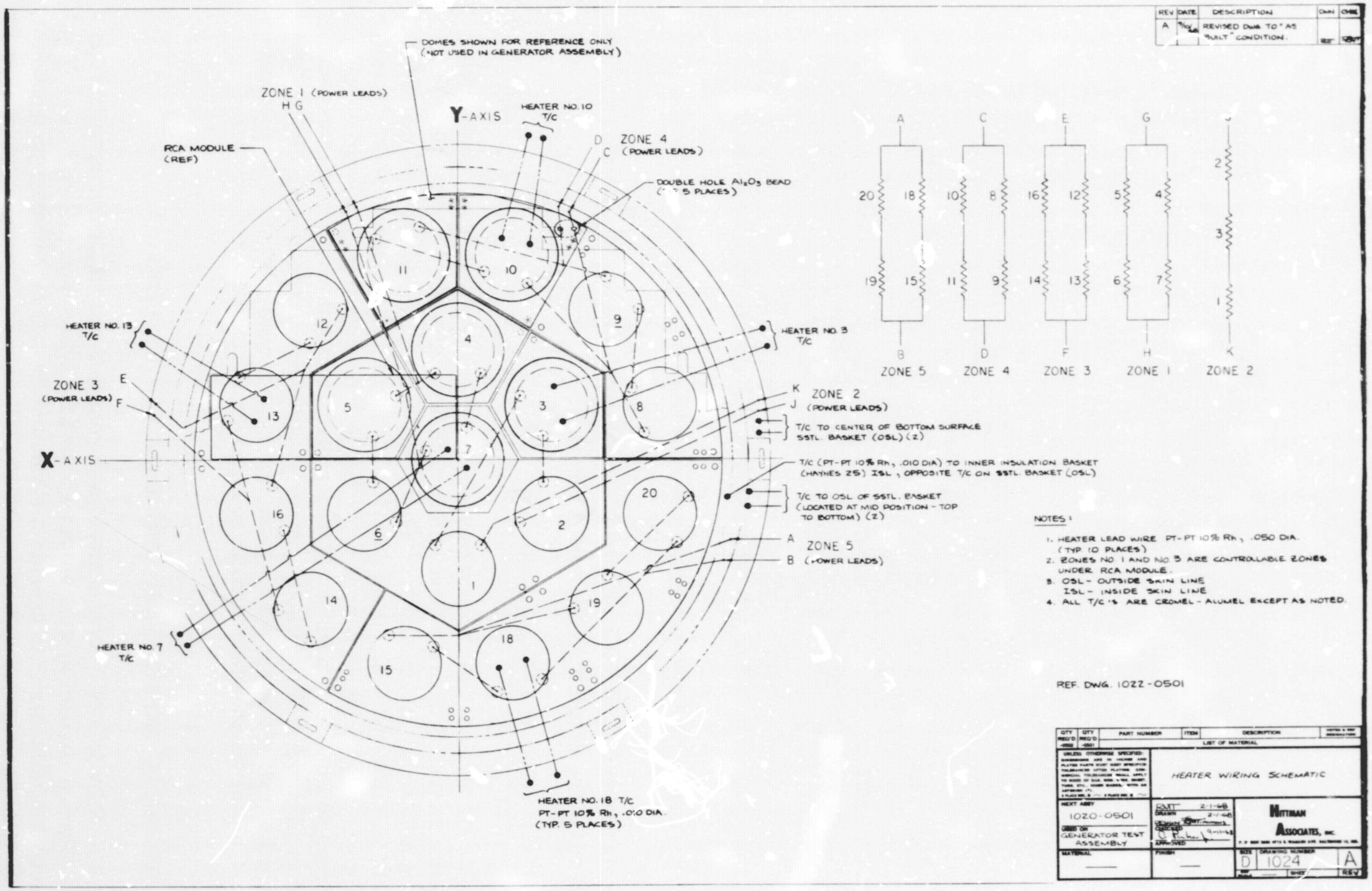

Figure 14. Heater Wiring Schematic

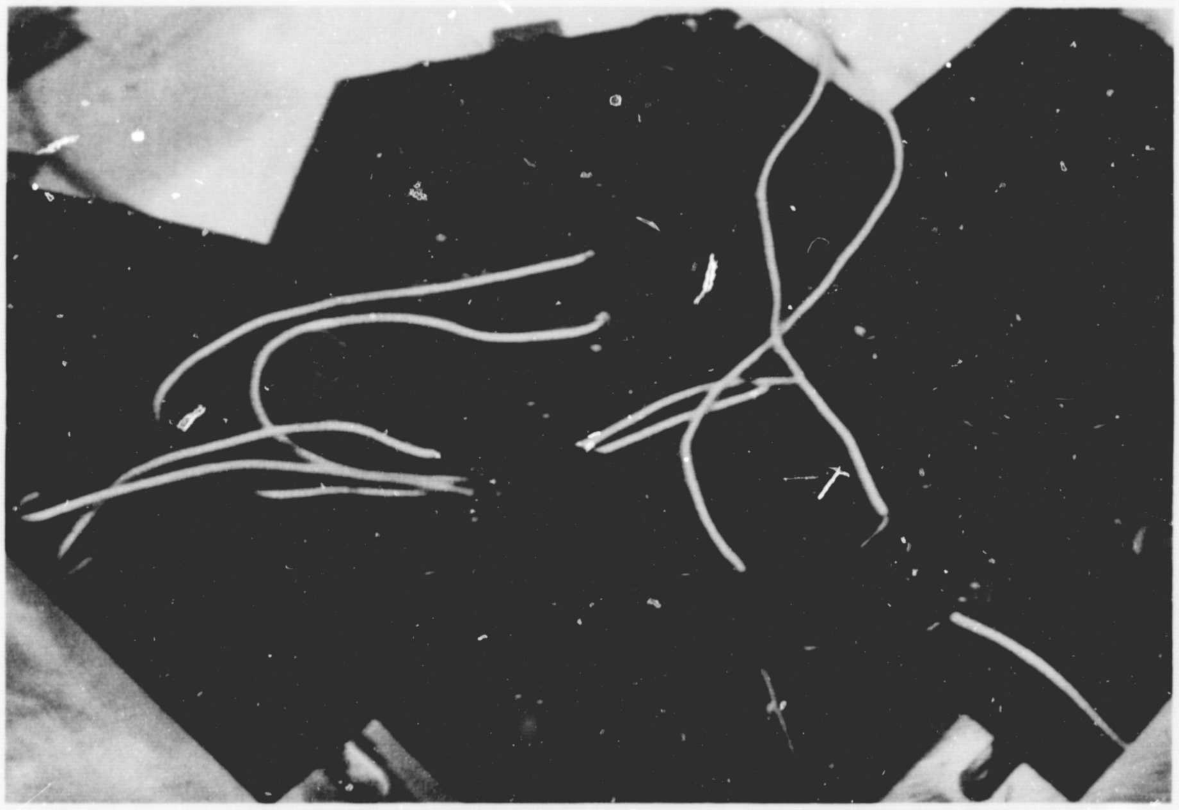

Figure 15. Installation of the Heater Assemblies in the Insulation Basket

The aluminum basket, H-Film, and Micro-Quartz are used to assemble a simulated pyrolytic graphite reentry heat shield.

G. Thermal Model Assembly

Two basic subassemblies comprise the NEW MOONS thermal model, the radiator assembly (Figure 2) and the heat source assembly (Figure 15). The completion of the model is made simply by joining these subassemblies. Figure 17 is a drawing of the thermal model. Figure 1 is a photograph of the system taken prior to the test sequence. The thermal model weight, including the instrumentation, is 60 pounds. Planar radiator generator design studies that have been performed for flight systems in the power range of the NEW MOONS thermal model yielded system weights that are comparable. This then became a design goal for the NEW MOONS system.

III. THERMAL MODEL TEST PROGRAM AND RESULTS

The NEW MOONS thermal model was designed and fabricated specifically for a thermal vacuum system test program with subsequent testing in air. The objective of the tests is to operate a simulated 75 watt thermoelectric generator

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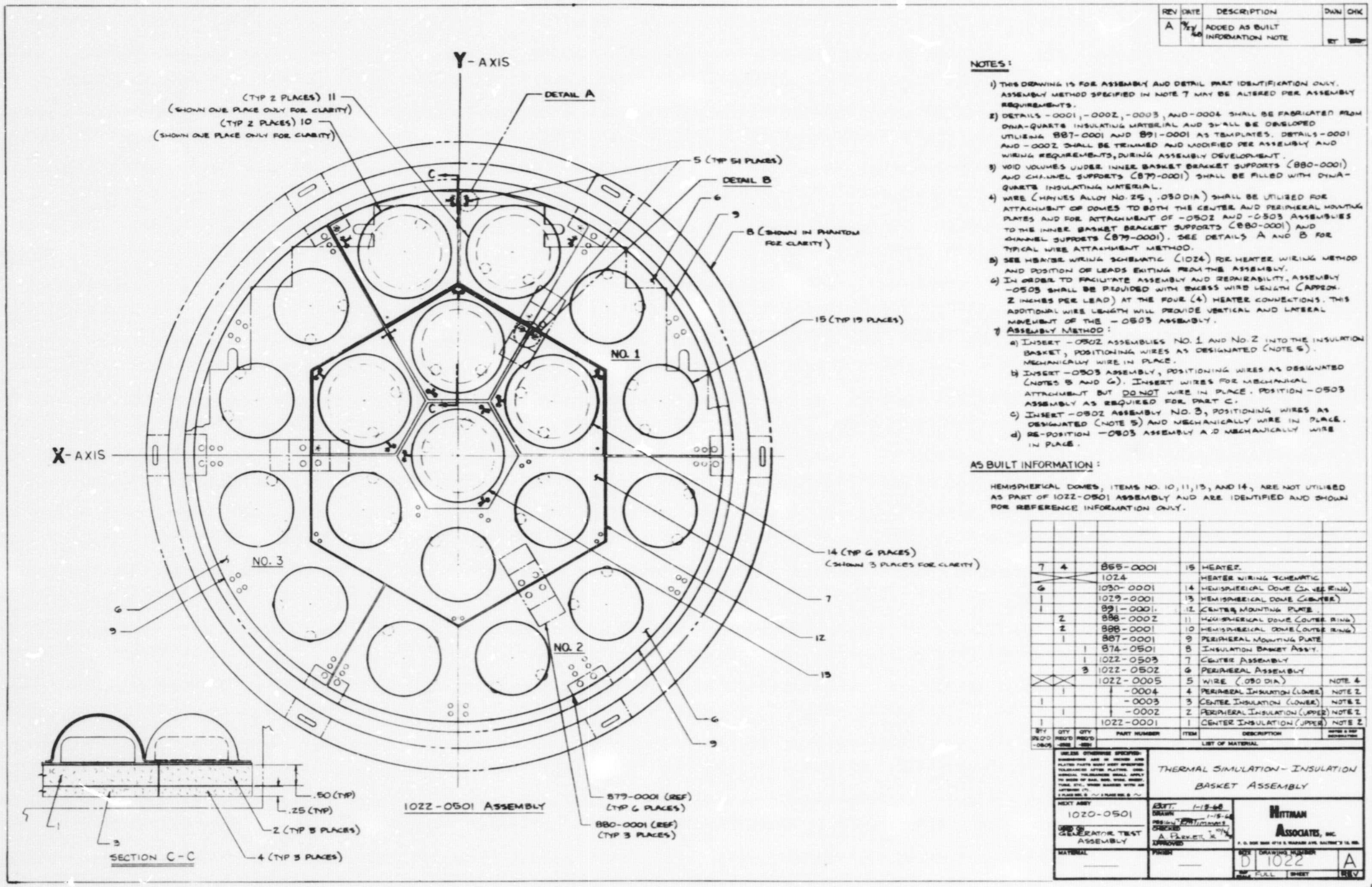

Figure 16. Thermal Simulation—Insulation Basket Assembly

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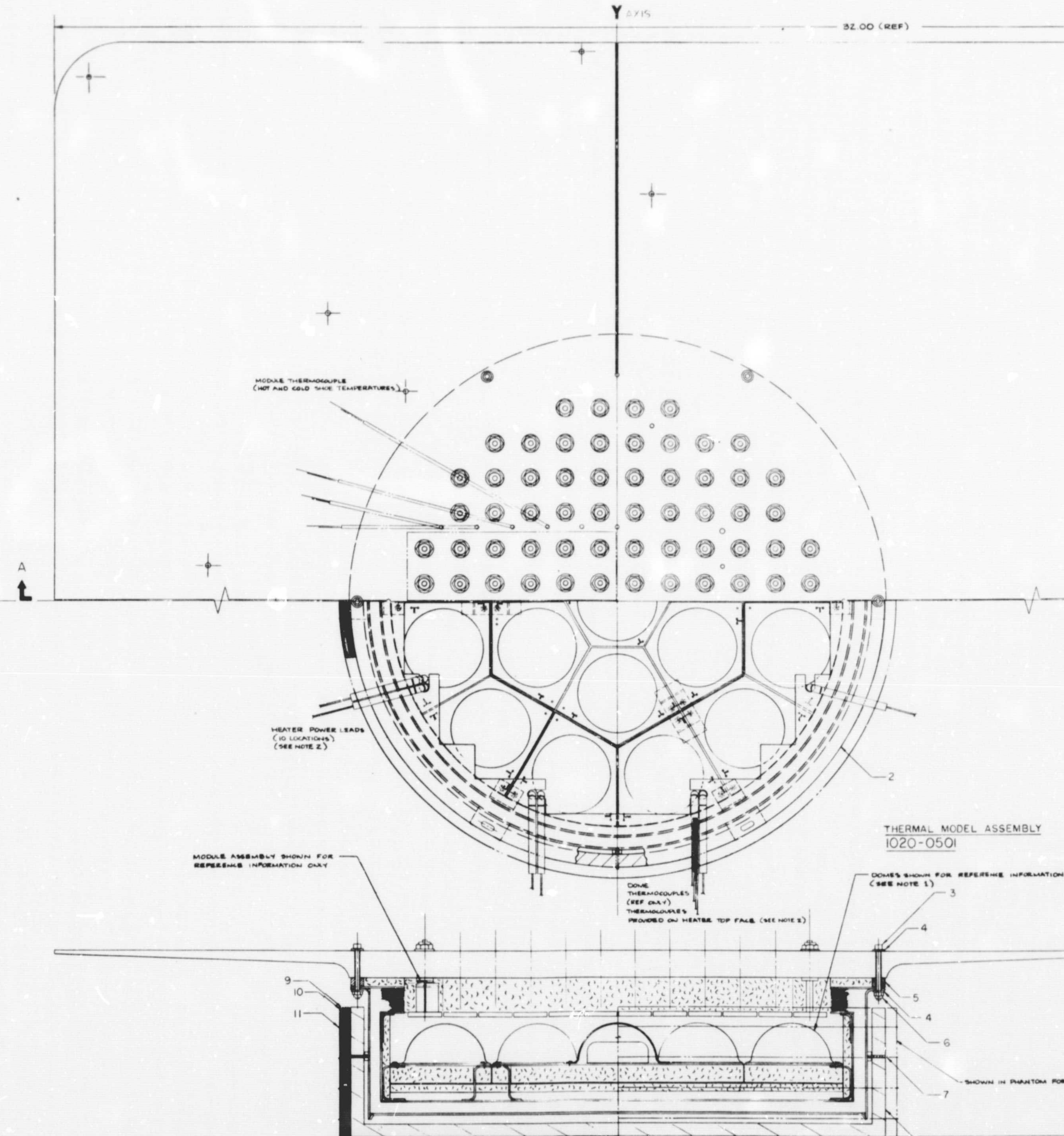

FOLDOUT FRAME #1

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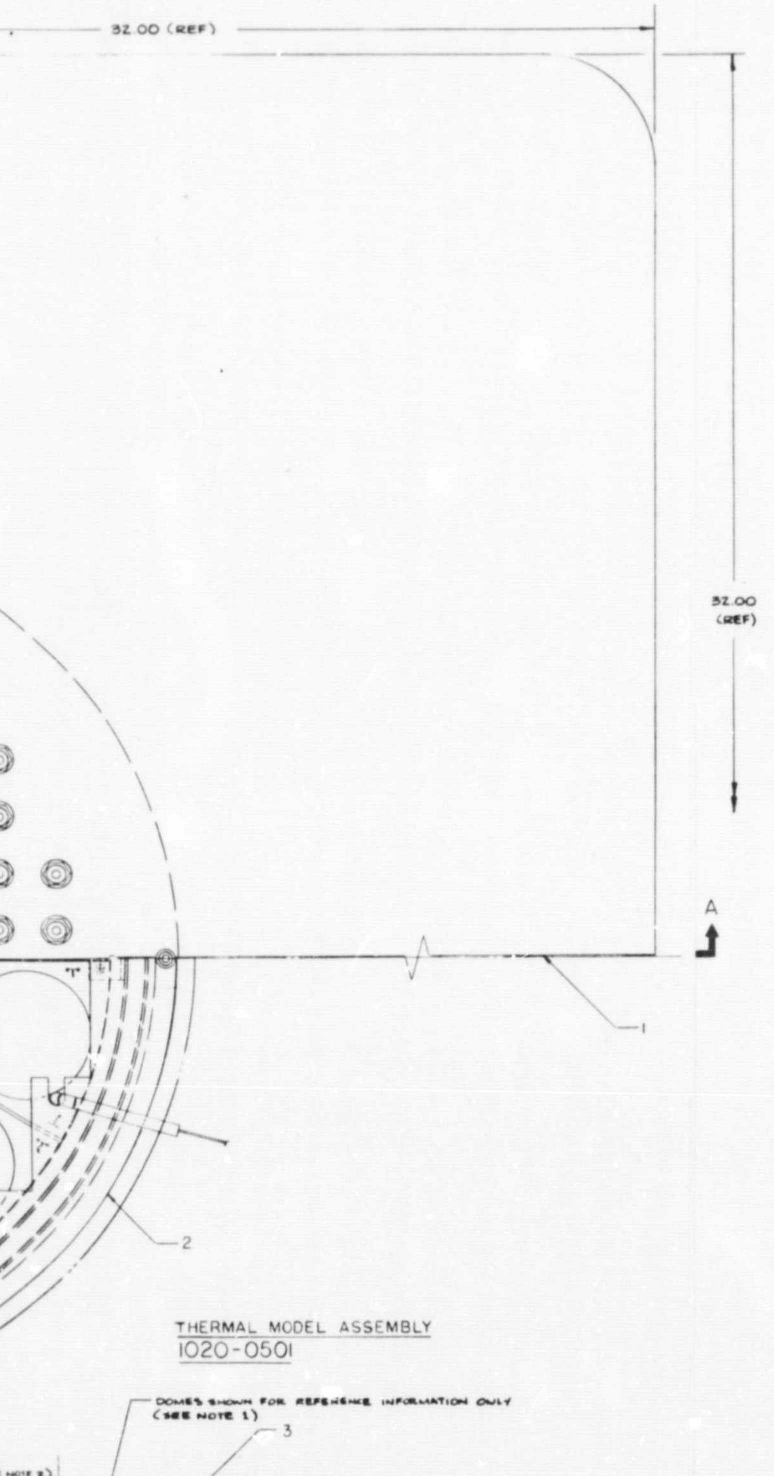

NOTES:

1. HEMISPHERICAL DOMES (DETAILS 888-0001 AND -0002, 1029-0001, AND 1030-0001) ARE NOT INSTALLED AS PART OF THERMAL SIMULATION – INSULATION BASKET ASSEMBLY (DWG. 1022-0501) AND ARE SHOWN FOR REFERENCE INFORMATION ONLY.
2. POWER AND THERMOCOUPLE LEADS SHOWN ARE FOR REFERENCE ONLY. SEE DWG. 1024 FOR ACTUAL LEAD PATHS AND EXIT LOCATIONS.
3. SEE HITTMAN ASSOCIATES DOCUMENT HIT-518 FOR "GENERATOR TEST ASSEMBLY" TEST PROGRAM PLAN.
4. ASSEMBLY OF RADIATOR THERMOPILE TO THERMAL SIMULATION – INSULATION BASKET:
   a. RADIATOR – THERMOPILE PREPARATION
      1) THE REMAINING EXPOSED RADIATOR SURFACE AT THE PERIMETER OF THE THERMOPILE (15.25 DIA.) IS TO BE INSULATED USING .25 INCH THICK DYNA-QUARTZ INSULATION.
      2) GROOVES ARE PROVIDED IN THE INSULATION FOR THERMOCOUPLE AND POWER LEAD EXIT PATHS.
      3) THERMOPILE AREA SHALL BE CLEANED AFTER INSULATION ASSEMBLY.
      4) ALL EXPOSED METAL SURFACES SHALL BE CLEANED AFTER ASSEMBLY (METHOL USED).
   b. INSULATION BASKET PREPARATION
      1) FIVE CIRCULAR PIECES EACH OF MICRO-QUARTZ FELT AND H-FILM ARE CUT AND PLACED ALTERNATELY BENEATH THE BASKET ASSEMBLY. EACH LAYER OF MICRO-QUARTZ FELT AND H-FILM SHALL BE INDIVIDUALLY WRAPPED AND POSITIONED. EACH WRAP IS HELD IN POSITION BY A DOUBLE TURN OF FIBERGLAS STRING. THE FIRST LAYER SHALL BE MICRO-QUARTZ FELT. THE FINAL LAYER SHALL BE H-FILM WHICH IS WRAPPED AND HELD IN POSITION BY FOUR INDIVIDUAL TURNS OF FIBERGLAS STRING.
   c. ASSEMBLY
      THE RADIATOR-THERMOPILE ASSEMBLY IS POSITIONED ABOVE THE INSULATION-BASKET ASSEMBLY AND SUPPORTED BY FOUR HAND OPERATED SCREW JACKS. ASSEMBLY GUIDE PINS ARE POSITIONED AT THE SIX ATTACHMENT POINTS ON THE BASKET ASSEMBLY. THE RADIATOR-THERMOPILE ASSEMBLY IS ALIGNED WITH THESE GUIDE PINS EXERCISING CARE TO ASSURE THAT THE X AND Y AXES ARE CORRECTLY POSITIONED. THE RADIATOR-THERMOPILE ASSEMBLY IS THEN LOWERED INTO THE BASKET ASSEMBLY UTILIZING THE SCREW JACKS. AFTER FINAL INSTALLATION, THE GUIDE PINS ARE REMOVED AND MOUNTING HARDWARE IS INSTALLED. TORQUE VALUE APPLIED TO ASSEMBLY HARDWARE SHALL NOT EXCEED 10 INCH POUNDS.

QTY REQ'D -0002	QTY REQ'D -0001	PART NUMBER	ITEM	DESCRIPTION	NOTES & REF DESIGNATION
		1024		HEATER WIRING SCHEMATIC	
			11	FIBERGLAS STRING (SEE NOTE 4)	
			10	H-FILM (SEE NOTE 4)	
			9	MICRO-QUARTZ FELT (SEE NOTE 4)	
	1	896-0001	8	SHIELD	
	4	79-012-062-0500	7	ROLLPIN (ESNA)	
	6	50FA-540	6	NUT (FLEXLOC) [illegible]	
	6	894-0001	5	SPACER	
	12	894-0002	4	WASHER	
	6	[illegible]	3	BOLT (STAINLESS STEEL)	
	1	1022-0501	2	THERMAL SIMULATION – INSULATION BASKET ASSY.	
	1	1021-0501	1	RADIATOR – THERMOPILE ASSY	

LIST OF MATERIAL

THERMAL MODEL ASSEMBLY

USED ON: GENERATOR TEST ASSEMBLY

HITTMAN ASSOCIATES, INC.

R 1020 B

Figure 17. Thermal Model Assembly

FOLDOUT FRAME #2

and compare empirical data with calculated design values. Some of the data points to be verified are as follows:

- Temperature distribution of the Si-Mo hot shoes across the radial distance of the thermal model
- Temperature profile across the heater basket during full power experiments
- Internal temperatures within the insulation barriers
- Temperature distribution across the beryllium radiator
- Electrical performance data to verify the conversion of heat to electricity
- Thermal input measurements to determine the amount of heat losses and power conversion

The thermal model was tested in a twelve by fifteen foot vacuum chamber at Goddard Space Flight Center (GSFC). The test sequence began on April 11, 1969 and was concluded on May 1, 1969. The following information will be presented in this section:

- Data to be collected
- Anticipated results
- Actual results

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A. Data to be Collected

Three types of instrumentation thermocouples are used. One type (chromel-alumel) senses temperatures in the range of 70°F to 800°F, the second type (tungsten-rhenium) measures temperatures in the range of 70°F to 1800°F, and the third type (platinum-platinum-rhodium) measures temperatures in the range of 70°F to 2000°F. By comparing the platinum-platinum-rhodium to the tungsten-rhenium readings, a cross check of relative temperatures is obtained early in life. Reasonable correlation can be obtained in the 1000°F to 1800°F range (anticipated within the first 24 hours of vacuum operation).

Several areas of the thermal model were selected for temperature profile measurements from the hottest point to the corresponding radiator position. The location and number of thermocouples are listed as follows:

Note: C/A—chromel-alumel, W/Re—tungsten-rhenium, and Pt/Pt-Rh—platinum-rhodium

Location	Number and Type of T/C
• Center heater of first heating zone	2 T/C: Pt/Pt-Rh
• Typical heater of second heating zone	2 T/C: Pt/Pt-Rh
• Typical heater of third heating zone	2 T/C: Pt/Pt-Rh
• Typical heater of fourth heating zone	2 T/C: Pt/Pt-Rh
• Typical heater of fifth heating zone	2 T/C: Pt/Pt-Rh

Note: Zones 3, 4, and 5 are the outer ring of 12 heaters; zones 1 and 2 represent the inner circle of seven heaters. Half of the T/Cs will be used to monitor or control the five heating zones.

• Si-Mo hot shoes in the 2×6 module	6 T/C: W/Re with Al_2O_3 Coating
• Dummy hot shoes in four locations	4 T/C: Pt/Pt-Rh
• Tungsten compensators in the 2×6 module	12 T/C: C/A at corresponding N and P cold sides of instrumented couples
• Steel stud at the six locations of the instrumented couples	6 T/C: C/A radiator position of SiGe module

• Temperature of Haynes-25 basket and outer stainless steel basket containing metal foil insulation	3 T/C: 2-C/A at exterior sidewall and bottom of outer stainless steel basket and 1 Pt/Pt-Rh at inside sidewall of Haynes-25 basket
• Beryllium radiator, locations at ten separate points	10 T/C: C/A at selected radiator positions

Total number of thermocouples is as follows:

Pt/Pt-Rh	=	15 units
W/Re	=	6 units
C/A	=	30 units

To control and measure the internal heat supplied to the thermal model, all electrical heater circuits are monitored with voltmeters, ammeters, and wattmeters. Five distinct circuits are required to control the 19 heaters. Each circuit is calibrated to determine the extraneous electrical losses prior to entry of the thermal model, (i.e., line losses, vacuum-feed through losses, and instrumentation error).

This corresponds to feed throughs of 116 pins which are sealed hermetically to maintain 10^{-6} torr vacuum.

B. Anticipated Results

Two categories of performance are evaluated, i.e., thermoelectric and thermal. A brief discussion of each area follows:

1. Thermoelectric Performance

A summary of the expected performance values for the 12 couple SiGe module are presented below. These values are based on a steady state average hot shoe temperature of 1490°F and radiator (or cold junction) temperature of 509°F. Approximately a 50°F temperature gradient exists between the thermoelement cold junction and the corresponding radiator location.

• Power	9.5 watts
• Open circuit voltage	1.63 volts

• Ratio of external resistance to internal resistance	1.15
• Load voltage	0.875 volts
• Optimum external resistance for maximum efficiency	81 milliohms
• Optimum load current	10.8 amps
• Internal resistance at temperature	70.5 milliohms
• Module efficiency	5.17 percent

The following data were measured during the testing program to evaluate thermoelectric performance:

During open circuit operation at design conditions:

- Open circuit voltage
- Internal resistance

During closed circuit operation at design conditions:

- Thermal model voltage
- Circuit current
- Voltage across load resistor

By using both open and closed circuit data, a reasonable check can be made on the performance of the SiGe module. For example, the maximum power from the module may be calculated from open circuit data as follows:

$$\text{Power} = \frac{(E_{oc})^2}{4R} = \frac{(1.63)^2}{4(0.0705)} = 9.5 \text{ watts}$$

Where, E_{oc} is open circuit voltage in volts, and R is the internal resistance in ohms.

A second method using closed circuit data is as follows:

$$\text{Power} = E_L(I) = 0.875(10.8) = 9.5 \text{ watts}$$

Where, E_L is the voltage at the terminals of the SiGe module in volts, and I is the circulating current in amperes.

By using a known resistance value in the external load circuit, the current can be calculated from the resistor voltage drop as follows:

$$I = \frac{E_R}{R_R}$$

This cross check verifies the measured current flowing through the ammeter.

There are some potential shortcomings to measuring the power output per module. For example, the external resistance for maximum efficiency is listed as 81 milliohms. The external resistance is measured from the (+) terminal of the thermal model through the outside loop to the (-) terminal of the thermal model. The outside loop is defined as follows:

- Power lead (0.85 V, 10.8 A) from (+) terminal to vacuum chamber bulkhead
- Hermetically sealed feed-through
- Power lead to calibrated resistor
- Calibrated resistor
- Ammeter lead
- Ammeter resistance
- Ammeter lead
- Power lead to bulkhead feed-through
- Hermetically sealed feed-through
- Power leads to (-) terminal of thermal model

In order to have a system with properly matched impedence, resistances of the above items must total no more than 81 milliohms. Normally, all resistances are pre-determined before the start of the tests, and the voltage across the calibrated resistor (R_R) is monitored throughout the test to verify the ammeter reading. Separate voltage measurements are made at the generator terminals during hot operation to determine open and closed circuit voltages. Multiplying the load voltage by the amperage yields delivered power for the thermal model.

The fallacy in this method of measuring power is that it may be impossible to match the load resistance with the internal resistance for maximum power transfer. However, opening up the external circuit and measuring the open circuit generator voltage and the internal resistance will provide data to approximate the maximum power.

$$P = \frac{(E_{oc})^2}{4R}$$

2. Thermal Performance

The anticipated thermal distribution of the NEW MOONS thermal model was predicted using a heat transfer code that was programmed for use on a UNIVAC-1108 digital computer. The heat transfer code, Thermal Analyzer Program, TAP-4, was modified for this problem. As the model is symmetrical about the x and y axes, a typical quadrant was investigated. The model was divided into approximately 125 nodes which involved about 500 connectors. As the primary mode of heat transfer is by radiation, a view factor (VIEWFAC) subroutine was utilized for these computations. The results of the analytical predictions are presented by Figures 18 through 22.

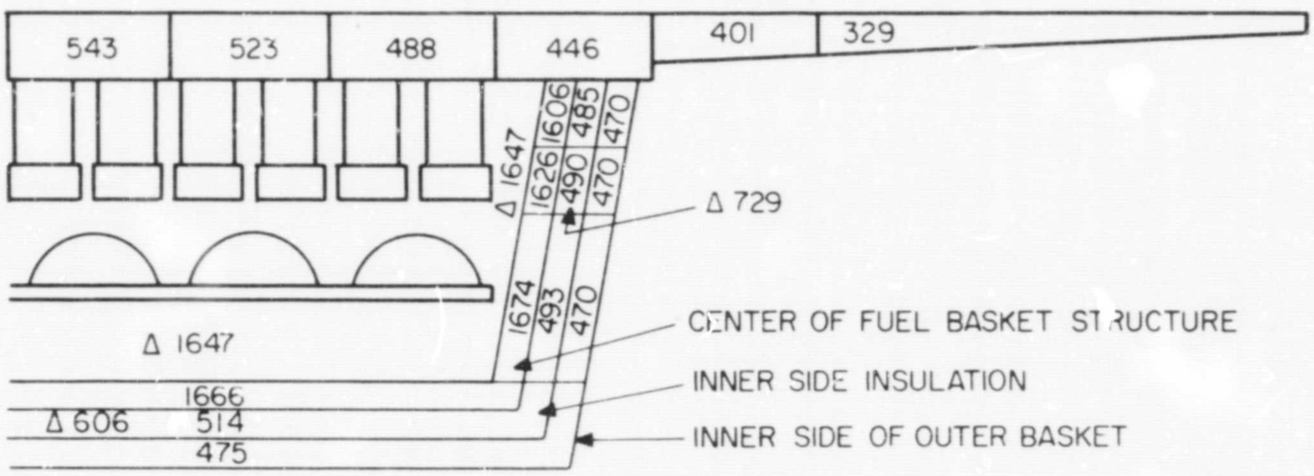
C. Actual Results

The measured test results for the two previously discussed categories follow:

1. Thermoelectric Performance

• Power	10.25 watts_{oc}, 8.56 watts_L
• Open circuit voltage	1.6723 volts
• Ratio of external resistance to internal resistance	1.415

(TEMPERATURES °F)



NOTES:

1880 WATTS TOTAL Δ 1677 WATTS TOTAL
RADIATOR EMISSIVITY = 0.8 Δ ~ 0.86
100 DUMMY T/Es (14.4 WATTS EACH)
12 LIVE T/Es (15.4 WATTS EACH) Δ 15.0
70°F AMBIENT ENVIRONMENT Δ 77°F
TYPICAL GENERATOR QUADRANT
* T/C NOT FUNCTIONAL DURING TEST
** NOT INSTRUMENTED
Δ MEASURED DATA POINT

Figure 18. Anticipated NEW MO[illegible] Thermal Model Test Temperature Distribution (Steady State Operation)

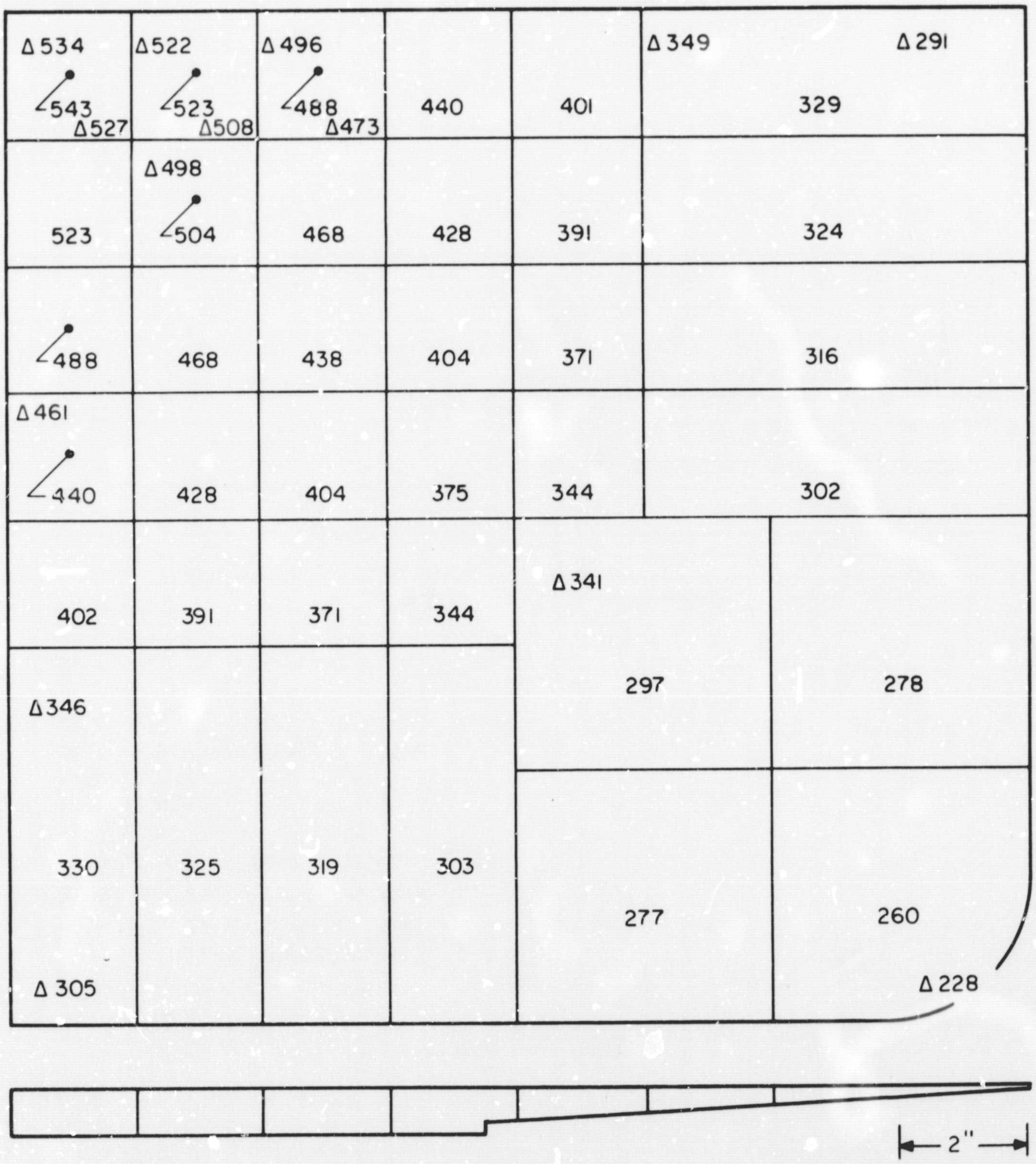


Figure 19. Estimated Radiator Temperature Profile (° F)

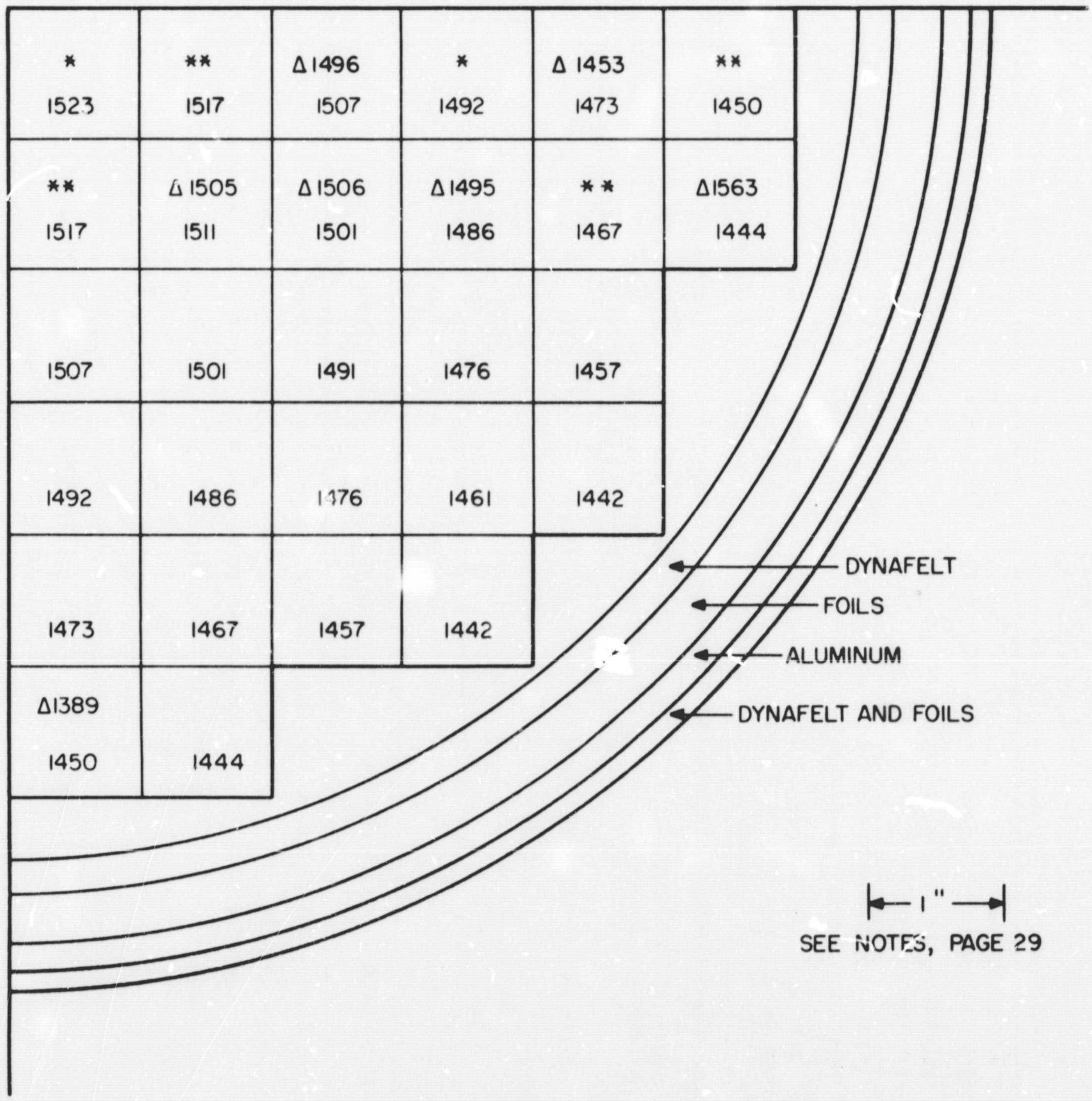


Figure 20. Estimated Hot Shoe Temperatures (°F)

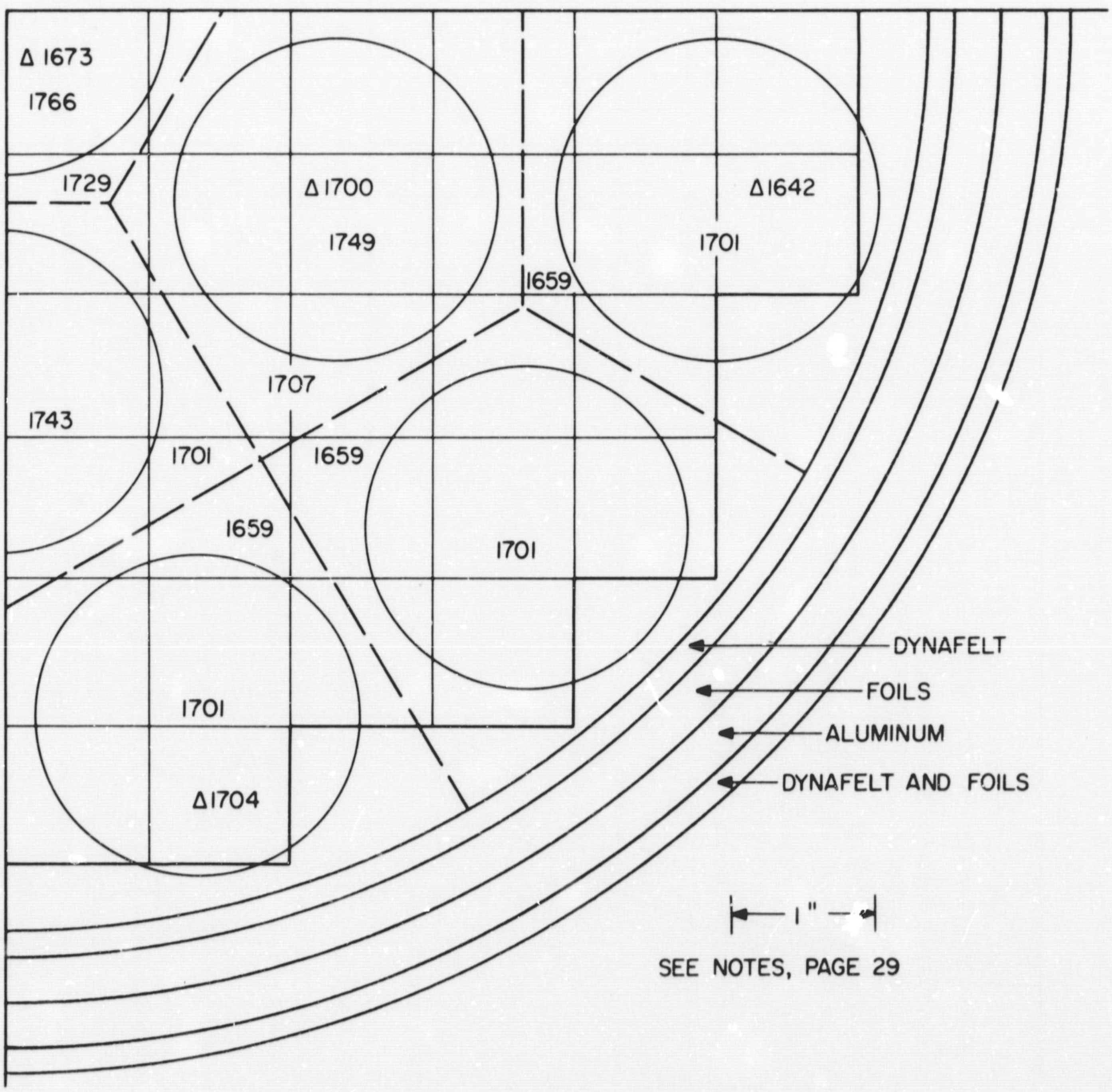
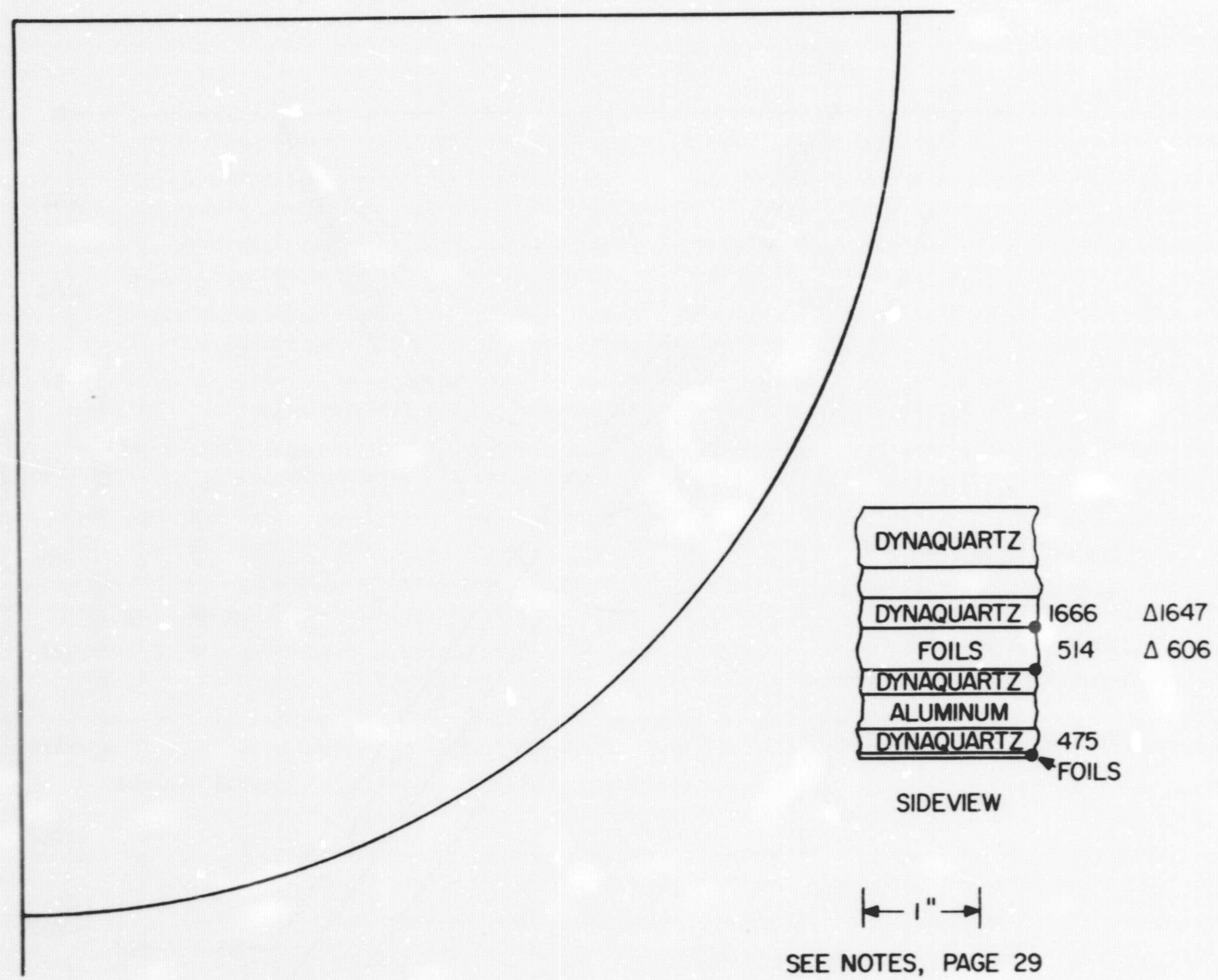


Figure 21. Estimated Heat Source Temperature (°F)



SEE NOTES, PAGE 29

Figure 22. Estimated Temperature Profile Through the Bottom Plate (°F)

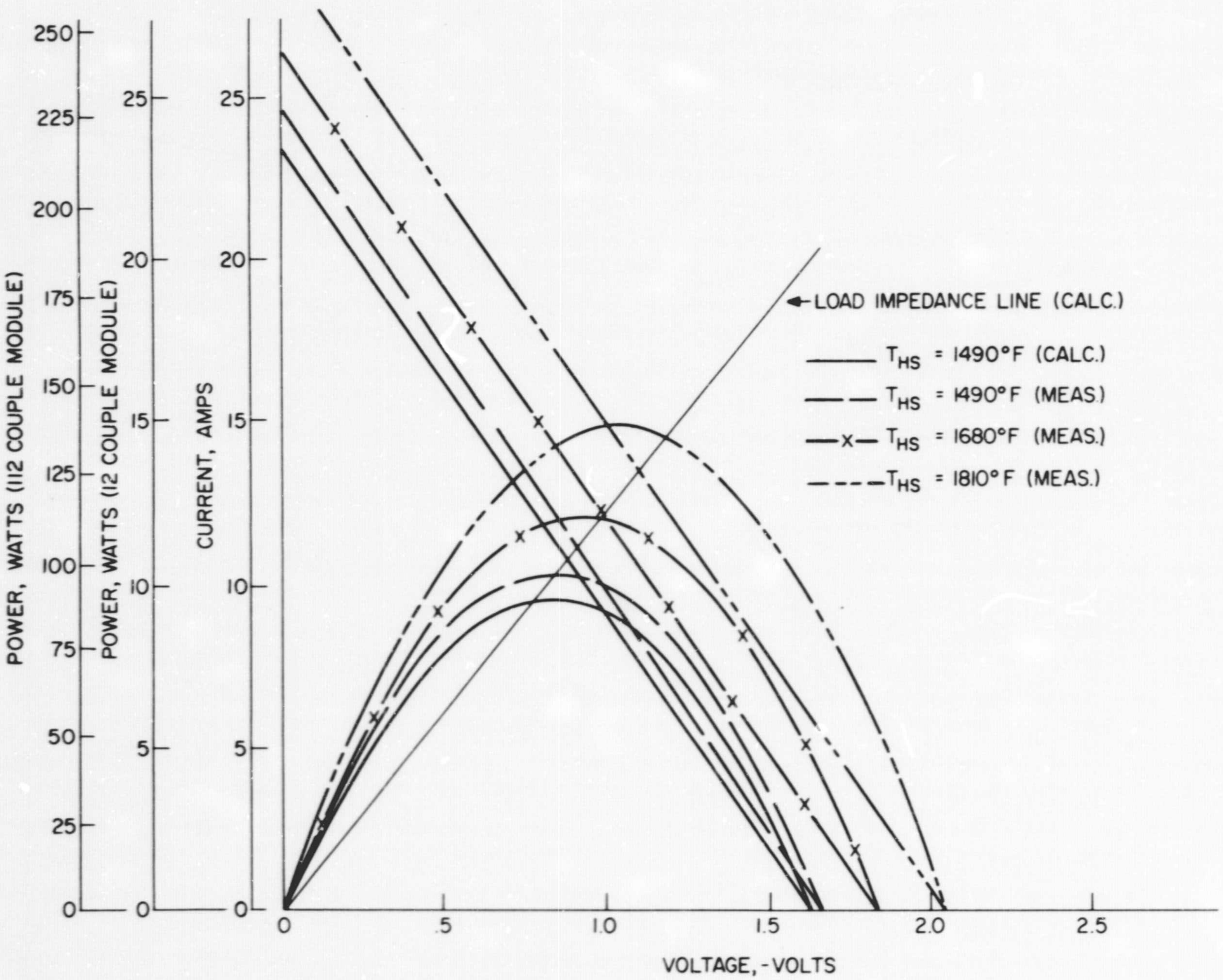


Figure 23. NEW MOONS Thermal Model Performance Data

- Load voltage 0.9113 volts
- External resistance* 97 milliohms
- Load circuit 9.396 amps
- Internal resistance at temperature 68.6 milliohms
- Apparent module efficiency 5.7 percent

The above data were obtained under the following operating parameters:

- Average steady state hot shoe temperature of 1490°F
- Average steady state radiator temperature of 508°F
- Vacuum is 10^{-7} torr
- Total input power to the heat source basket (including all losses) of 1677 watts

The thermal model performance data are summarized by Figure 23.

2. Thermal Performance

The measured vacuum operating steady state temperature distribution of the thermal model is given on Figures 18 through 22. The test values are indicated with the following symbol, △.

3. Air Operation

At the conclusion of the vacuum testing of the thermal model, the system was operated in an air environment at about the same input power level. The system was operated until equilibrium conditions were reached. Data were collected and compared with the vacuum equilibrium points. The results obtained for the thermopile performance follow:

- Power 3.93 $watts_L$

*This is the minimum value that was achieved in the external (or load) circuit. In order to obtain a matched load or maximum power point the external resistance value had to be about 79 milliohms. As previously discussed, the maximum power point can be calculated using open circuit data. Thus, the calculated open circuit power value of 10.25 watts indicates the potential of the system while the load power value of 8.56 watts is the maximum obtainable under the above test conditions.

- Open circuit voltage —
- Ratio of external resistance to internal resistance —
- Load voltage 0.5633 volts
- External resistance 81 milliohms
- Load current 6.986 amps
- Internal resistance at temperature —
- Ratio: $\frac{\text{Air Operation}}{\text{Vacuum Operation}}$ 0.474

The primary insulation of the NEW MOONS thermal model is the platinum multi-foil vacuum assembly. Therefore, the difference in the system performance relates to the efficiency of this component in air. The above data were obtained under the following operating parameters:

- Average steady state hot shoe temperature of 1055°F
- Average steady state radiator temperature of 396°F
- Total input power to the heat source basket of 1624 watts

IV. CONCLUSIONS

The following conclusions and observations are made relevant to the design, fabrication, and test of the NEW MOONS thermal model to establish feasibility of the concept.

- To date, all test data indicate that the planar concept is feasible insofar as design, fabrication and performance are concerned.
- Throughout the range of interest, the thermopile performance was close to that predicted (nominal predicted 9.5 watts, actual 10.25 watts)
- Throughout the range of interest, the temperature gradients were near the predicted values (see Figures 18 through 22)

- The use of typical flight system's materials in the thermal model confirmed the practicability of hardware fabrication. The beryllium radiator and the platinum multi-foil vacuum insulation basket were fabricated and tested without incidence. Further, the use of typical materials established a higher degree of confidence in data for the model insofar as it may relate to an actual system.

- All components performed as anticipated.

- The calculated power for a complete thermopile operating at the test conditions is approximately 95 watts (electric), see Figure 23. The apparent power density is about 1.6 watts/pound.

- The system operation in air yields approximately 50 percent of the systems performance in vacuum. Thus sufficient power appears to be available to verify generator performance in a pre-launch mode of operation; however the voltage may be different for space operation. This may necessitate an additional power source element.

- At the conclusion of the test sequence, the system was operated in vacuum at an average hot shoe temperature of 1832°F (1000°C) and steady state performance data were obtained. The 12 couple module produced a load power value of 12.4 watts. This results in an indicated power increase of about 45 percent. These data extrapolate to the following:

  (1) Open circuit 12 couple module power output of about 14.5 watts (see Figure 23)

  (2) Generator total power output of about 139 watts (electric)

  (3) Conversion efficiency of $\sim$6.8 percent

  (4) Power density of $\sim$2.3 watts/pound

To summarize, the test program was completely successful and the test objectives were satisfied by the demonstration.

V. ACKNOWLEDGMENTS

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